3D Equilibria and Energetic Particle Physics on MST

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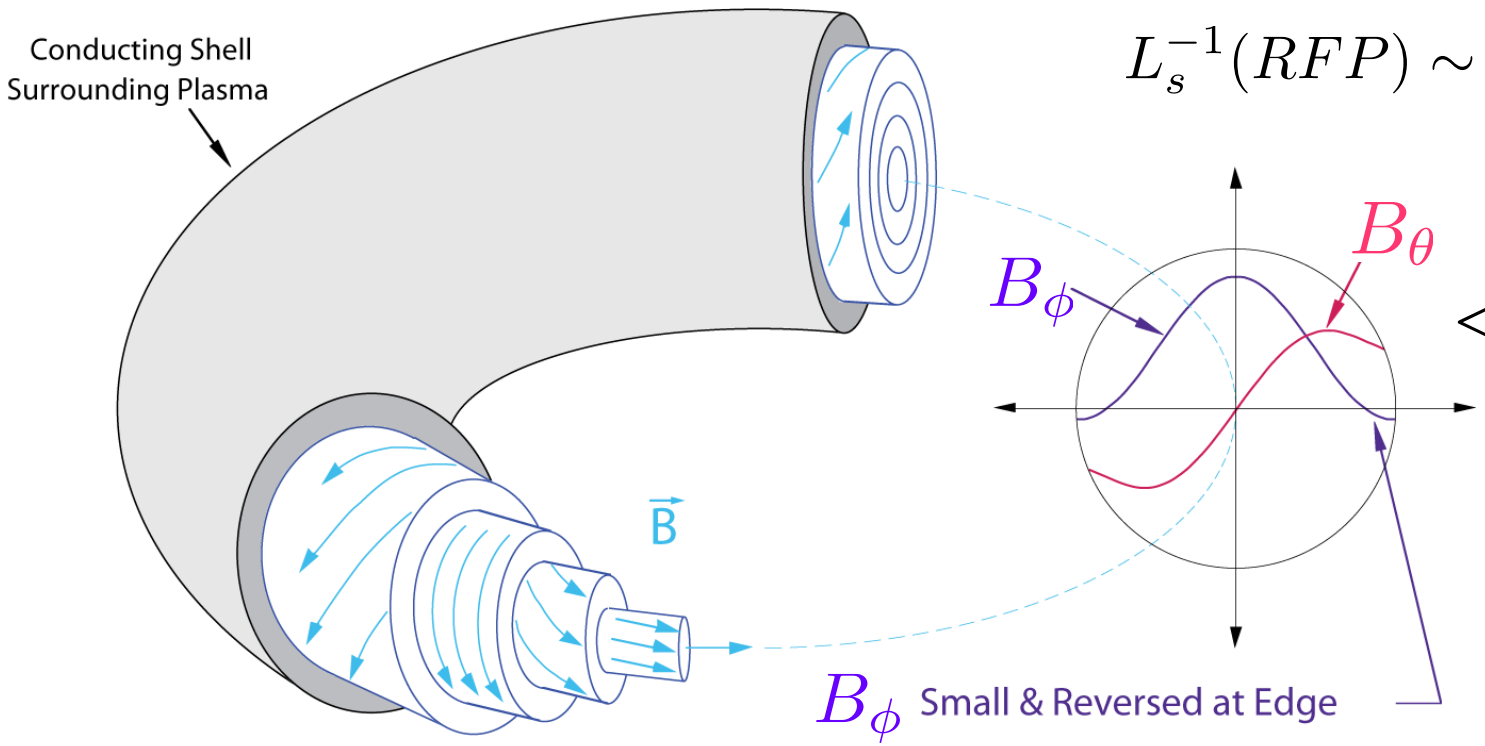
Fast Ions and 3D Fields: Motivations

- 3D equilibria in RFPs are a new field of study
  - No RFPs designed specifically to generate a Single Helical Axis (SHAx)
  - Internal diagnostics and equilibrium solvers are critical to understanding plasma behavior
- How does broken axisymmetry affect fast ions?
  - Presents new challenges for diagnostics
  - Plasma properties are altered
    - Field stochasticity reduced
    - Mode rotation halted
    - "Non-Optimized Stellarator" ?
- Transport in these equilibria is a critical question!
  - As well as other properties

Talk Overview

- Fast Ion Confinement on the Reversed Field Pinch (RFP)
  - RFP description
  - Madison Symmetric Torus (MST)
  - Neutral beam and diagnostics
    - Previous Confinement studies
    - Fast Ion Effects in MST plasmas
- Initial Fast Ion Studies in 3D Equilibria
  - Transition to 3D
    - Properties of the helical RFP
  - Fast Ion Confinement in 3D fields
  - Fast Ion effects and 3D fields
- 3D Equilibrium Reconstruction
  - V3FIT/VMEC

The Reversed Field Pinch (RFP)



$$L_s^{-1}(RFP) \sim -7 \times L_s^{-1}(Tokamak)$$

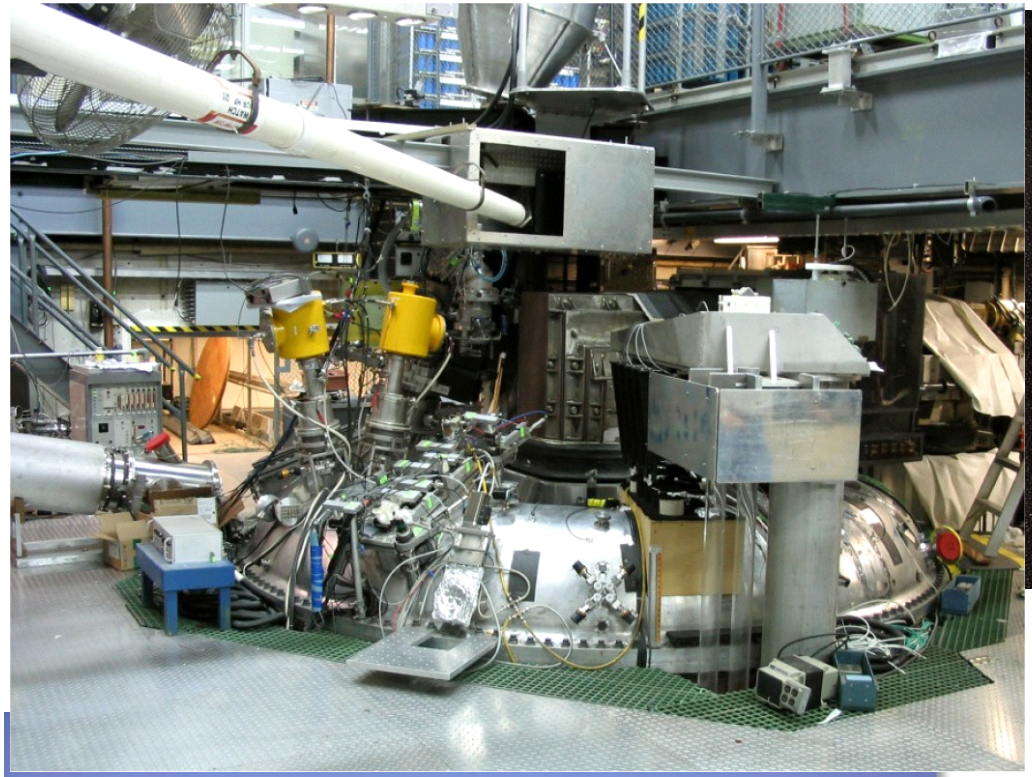
$$< B_\phi > \approx < B_\theta >$$

Reversed Field: Wall toroidal field is zero or antiparallel to core toroidal field (and small).

$$\boxed{\vec{B}(0) \perp \vec{B}(a)}$$

- Fast ion behavior effects
- Diagnostics and the "RFP phase space" problem

Madison Symmetric Torus



Parameters

$R = 1.5$ m $a = 0.52$ m

$I_P = 200\text{-}600$ kA

$n_e \sim 10^{13}$ cm^{-3}

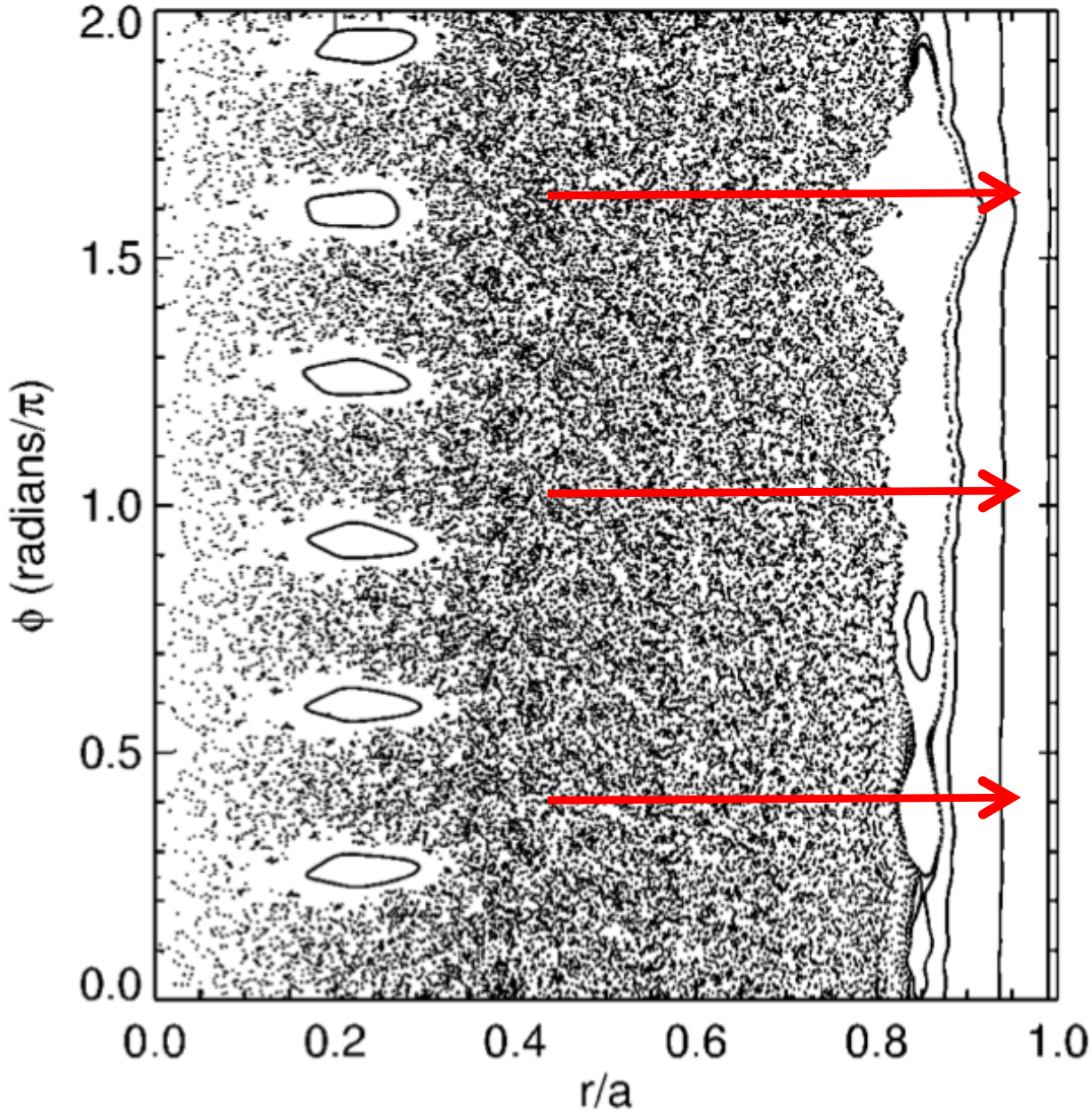
$T_e \leq 2$ keV

$B_\phi, B_\theta \sim 0.5$ T

$q_0 \leq 0.24$

$(m,n)_R = (1,5)$ or $(1,6)$

Stochastic magnetic field reduces confinement

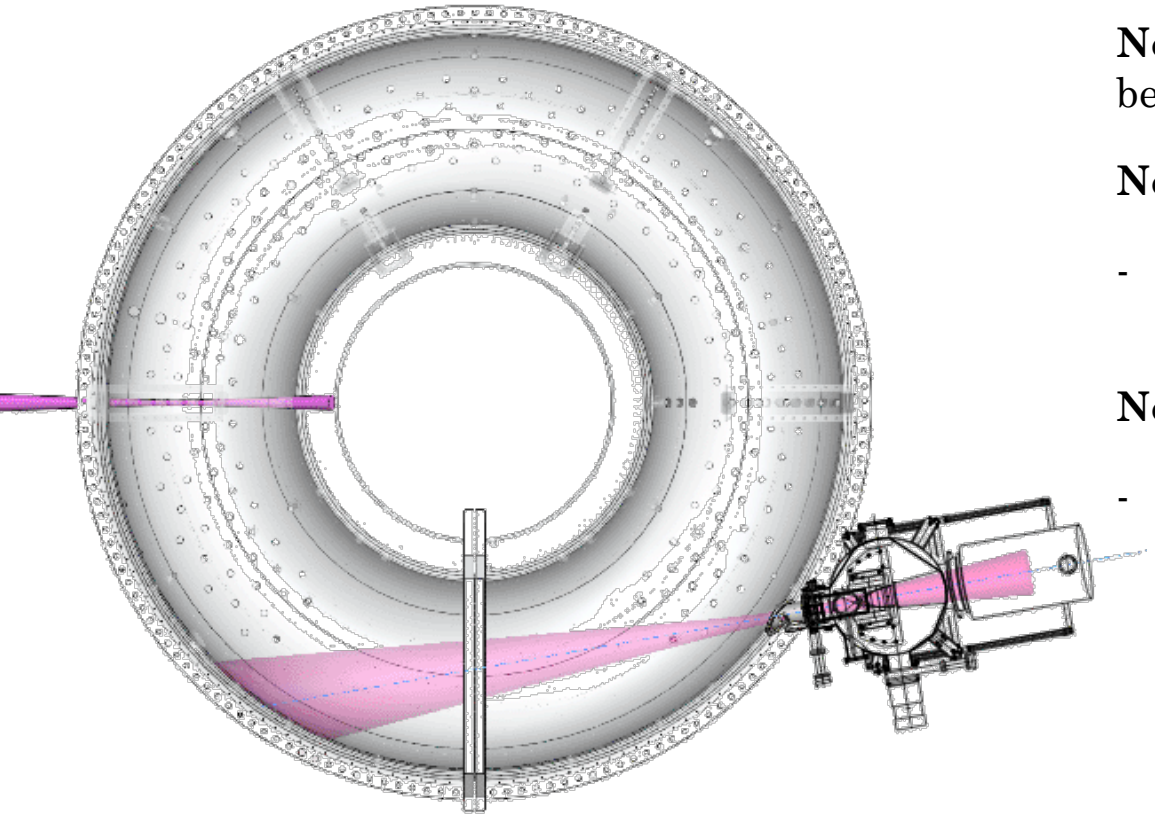


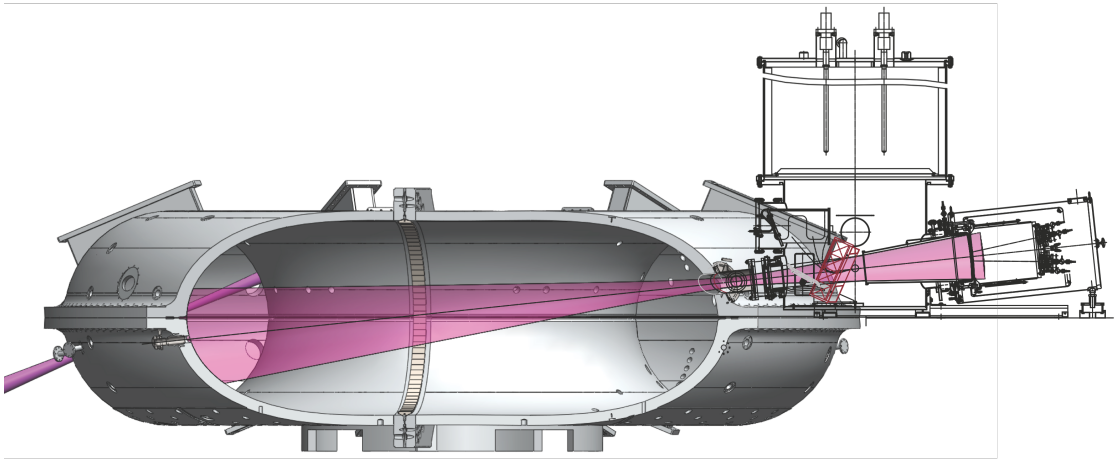
- Tearing modes result in magnetic islands at resonant surfaces
- Stochastic fields are created by overlapping magnetic islands outside of the plasma core
- - Transport will be high according to Rechester-Rosenbluth formalism

$$\tau_e \approx 1 - 2 \text{ ms}$$

T. M. Biewer *et al.* PRL (2003)

Neutral beam injection on MST





Neutral Beam: Injected tangentially on-axis. Can be co- or counter-injected by flipping I_P

Neutron Detecter: Scintillator-based diagnostic

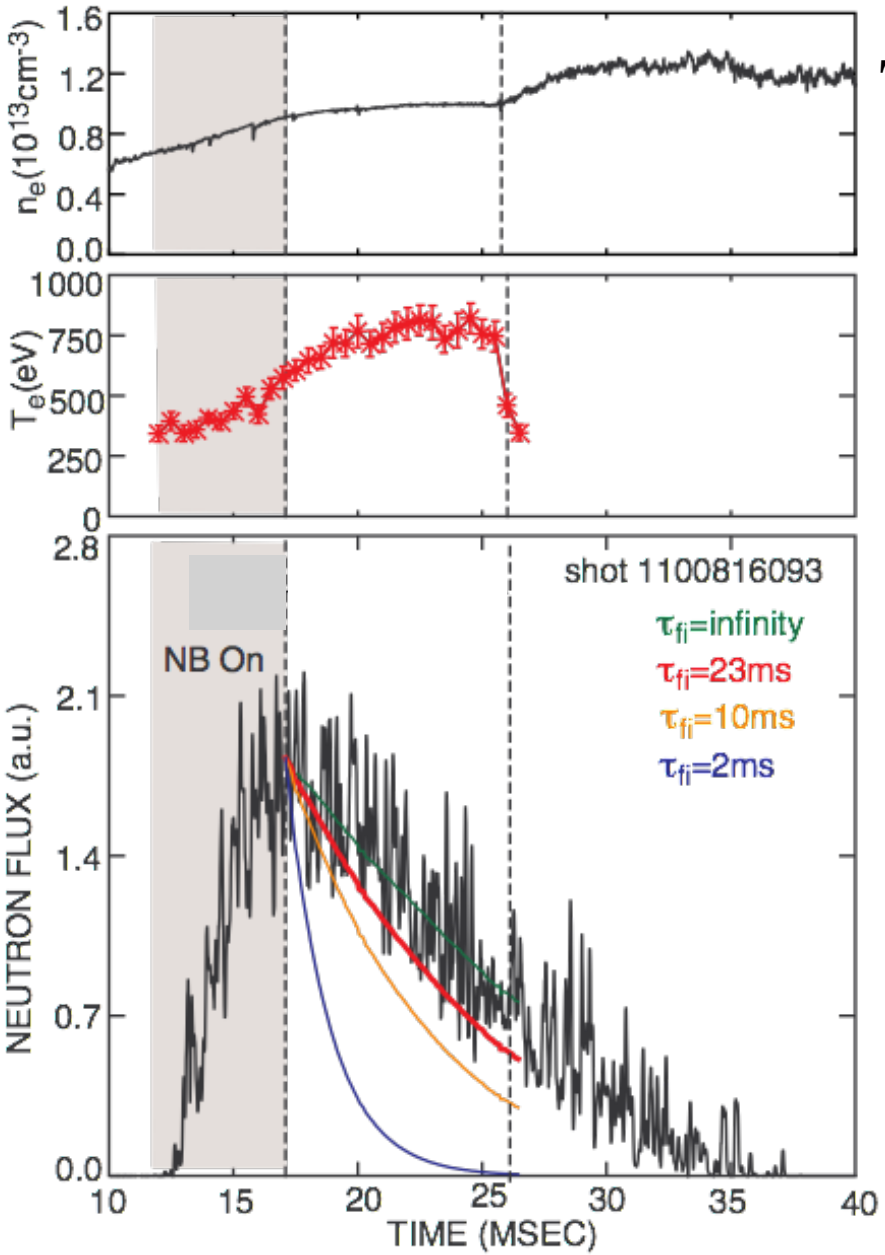
- Measures D-D beam-target reactions from Deuterium doping

Neutral Particle Analyzer

- Measures neutral products of charge exchange. 20 channels; 10 Hydrogen, 10 Deuterium; From 1-30+ keV

NBI Parameter	Specification
Beam Energy	25 keV
Beam Power	1 MW
Pulse Length	20 ms
Composition	95-97% H, 3-5% D
Energy Fraction (E:E/2:E/3:E/18)	86%:10%:2%:2%

Beam blip method measures fast ion confinement time



Turn off beam and measure neutron rate decay.

Neutron decay is a product of fast ion loss and slowing down:

$$\Gamma_n(t) \propto \int_V \boxed{n_{fi}(t)} n_i(t) \boxed{< \sigma_{dd}\left(E_{fi}(t)\right) v_{fi}(t) >} \, \mathrm{d}V$$

Or:

$$\frac{1}{\tau_{n-exp}} \approx \boxed{\frac{1}{\tau_{fi}}} + \boxed{\frac{1}{\tau_{n-classical}}}$$

with $\tau_{n-classical}$ calculated from classical slowing-down theory.

Magnetic bursts excluded from the analysis:

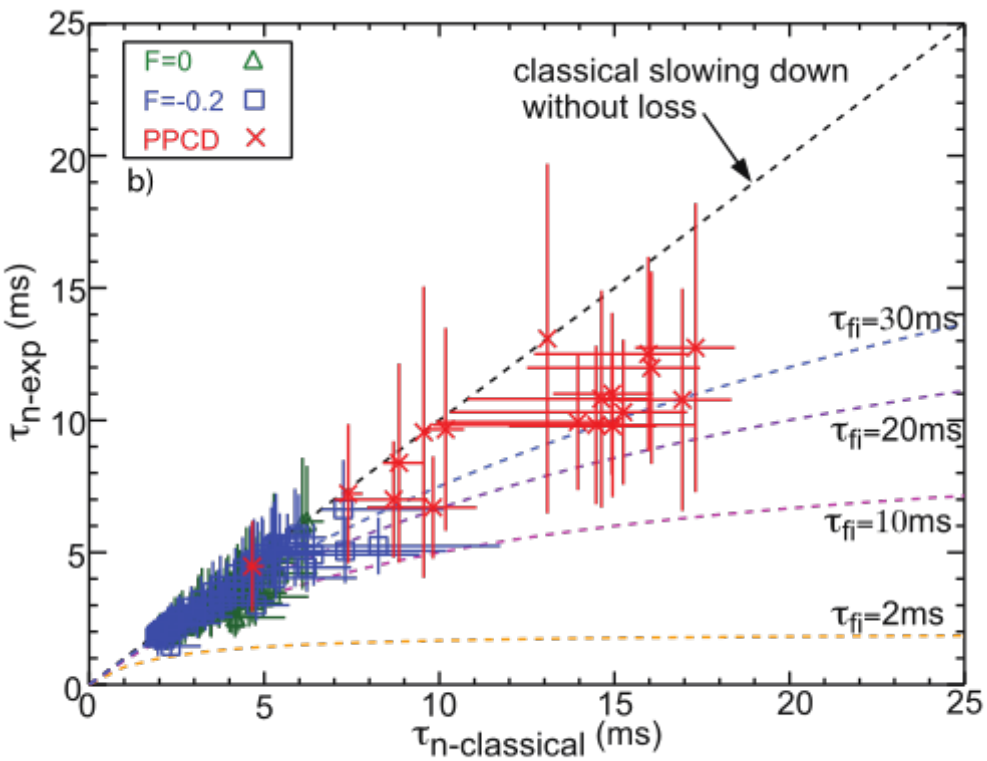
- Strong reconnection events explicitly excluded

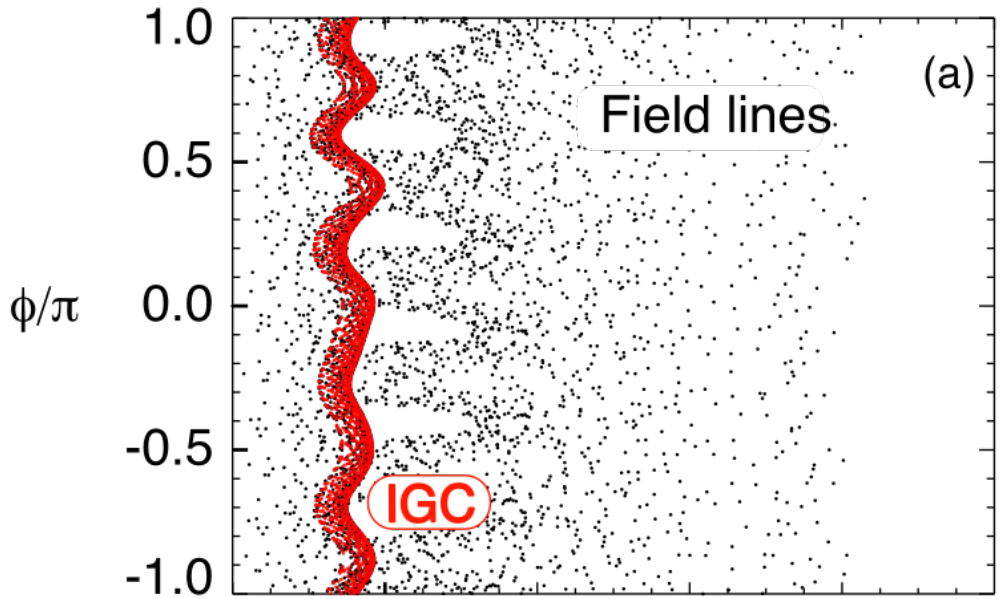
- Alfvénic activity terminates shortly (≈ 1 ms) after beam turn-off

Fast ions are confined near-classically despite stochastic fields

	τ_{fi}	$\tau_{i,thermal}$
Standard	10 ms	1-2 ms
Improved Confinement	25 ms	10 ms

Fast ion confinement time is longer than thermal particle and energy confinement time





Ion Guiding Center calculation shows that fast ions average over magnetic field

- Insensitive to islands and stochastic fields

Fast ions behave near-classically:

$$\tau_{n-exp} \sim \tau_{n-classical}$$

G. Fiksel *et al.* PRL (2005)

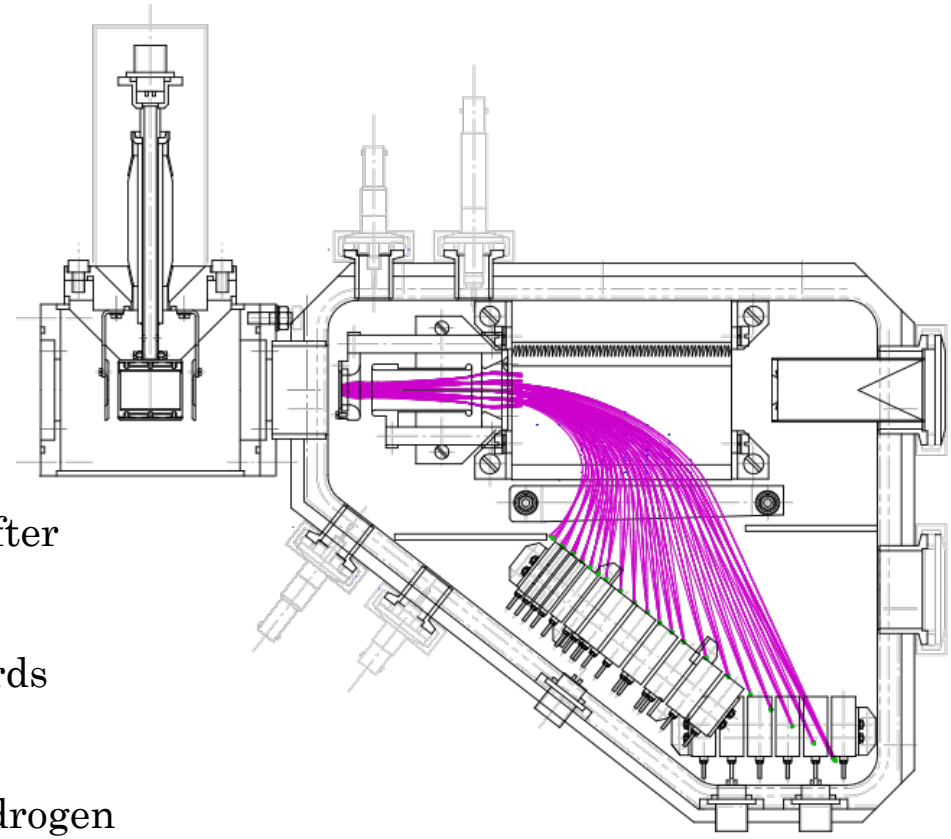
Neutral Particle Analyzer confirms slowing down of fast ions

E: 1-35 keV

ΔE: 2-3 keV

Δt: ~ 0.1 ms

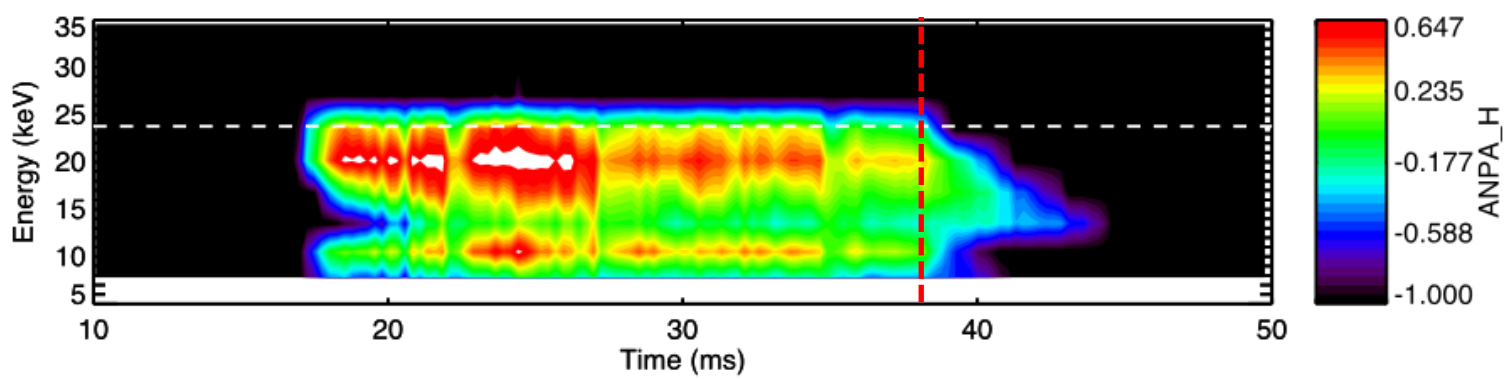
Tangential View



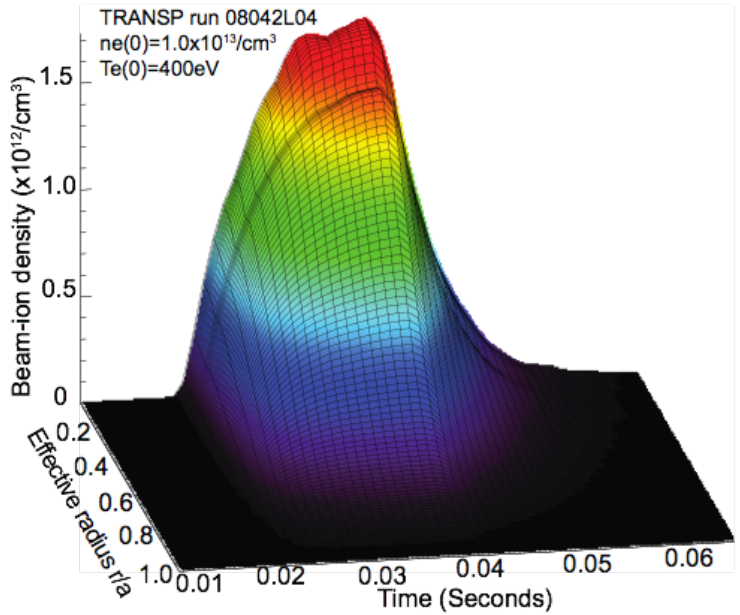
Hydrogen charge exchange signals persist for ≈ 5 ms after NBI turn-off. Indicates good fast ion confinement.

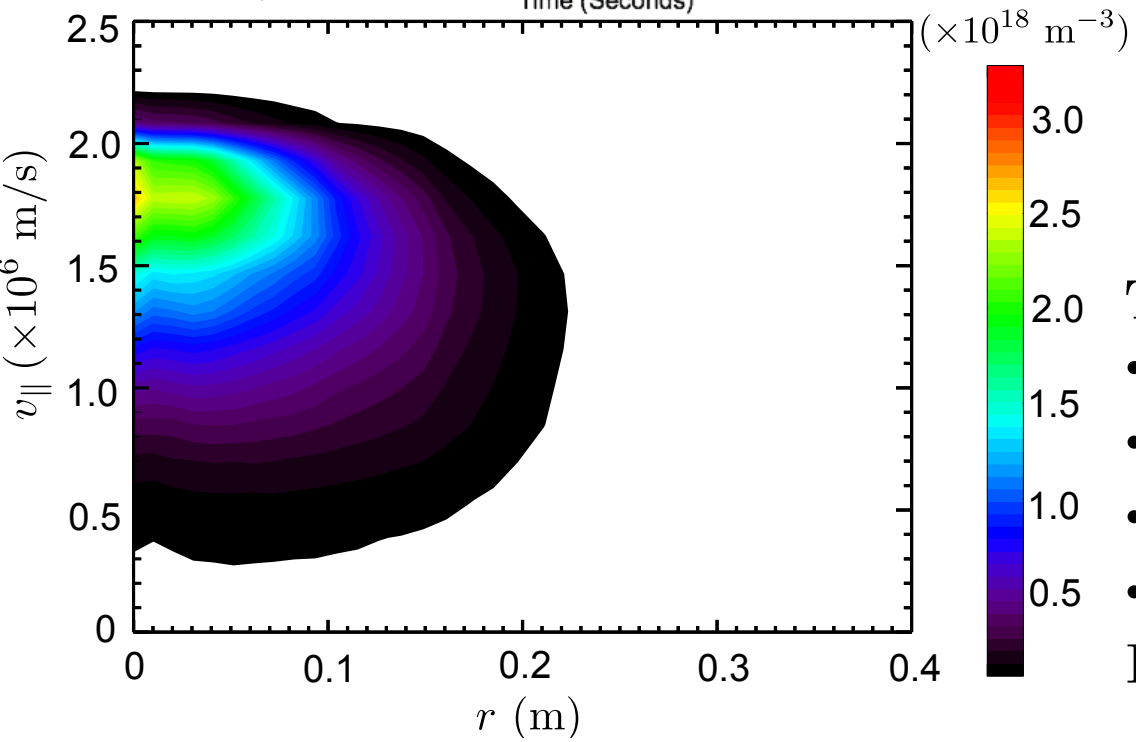
Neutron Detector: Volume-averaged, weighted towards passing fast Deuterium ions in the core.

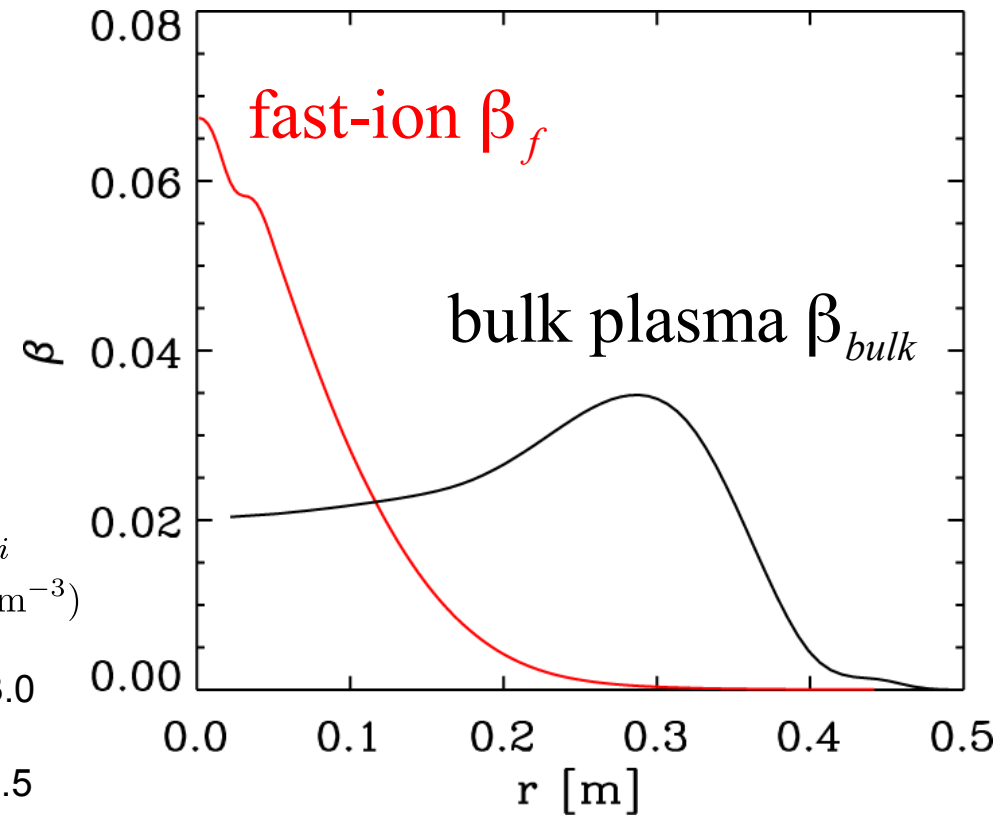
NPA: Charge Exchange, mainly from high $v_{||}$ fast Hydrogen ions in the core (for this view).



TRANSP predicts large fast ion content (classical, upper bound.)





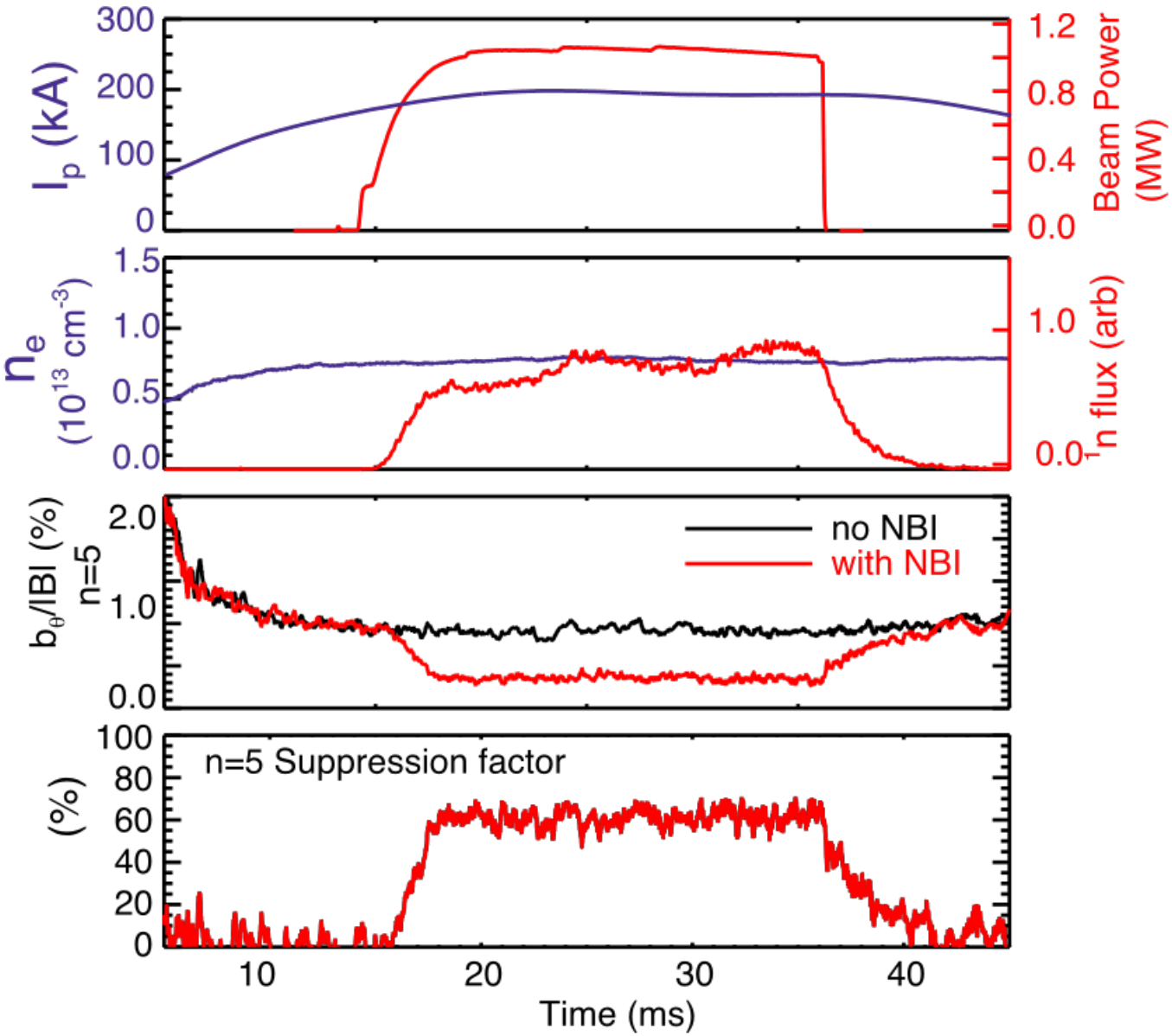


TRANSP predicts:

- super-Alfvenic distribution; large $\nabla v_{||}$
- High $v_{||}/v$
- $n_{fi}/n_e \sim$ 15-25%
- $\beta_f > \beta_{bulk}$ locally; large gradient.

Free energy available.

Fast ions have stabilizing influence on core tearing mode



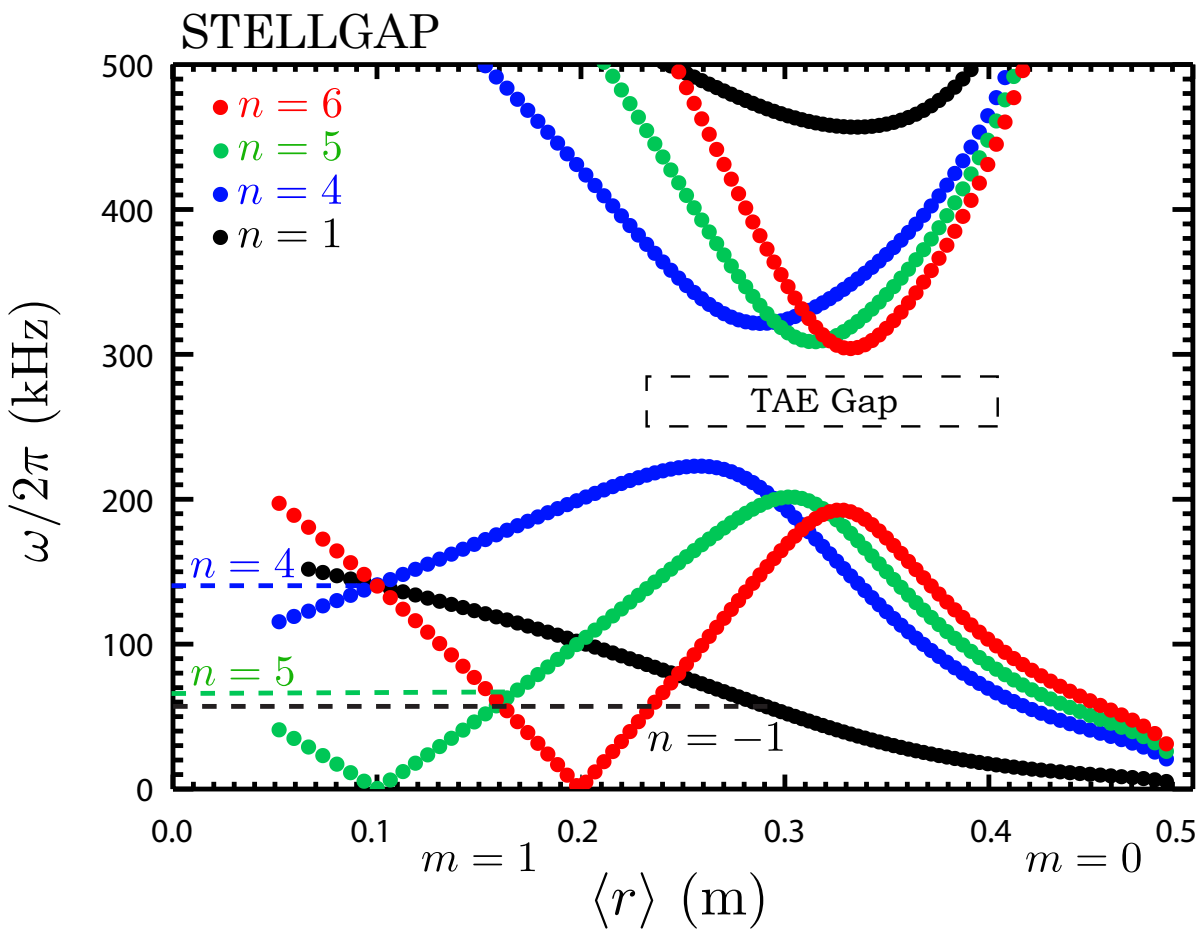
- Low I_p discharges studied.
- Several discharges averaged (fixed I_p, n_e) to reduce statistical noise
- n=5 (core-most) mode amplitude sharply reduced
- Other modes weakly affected

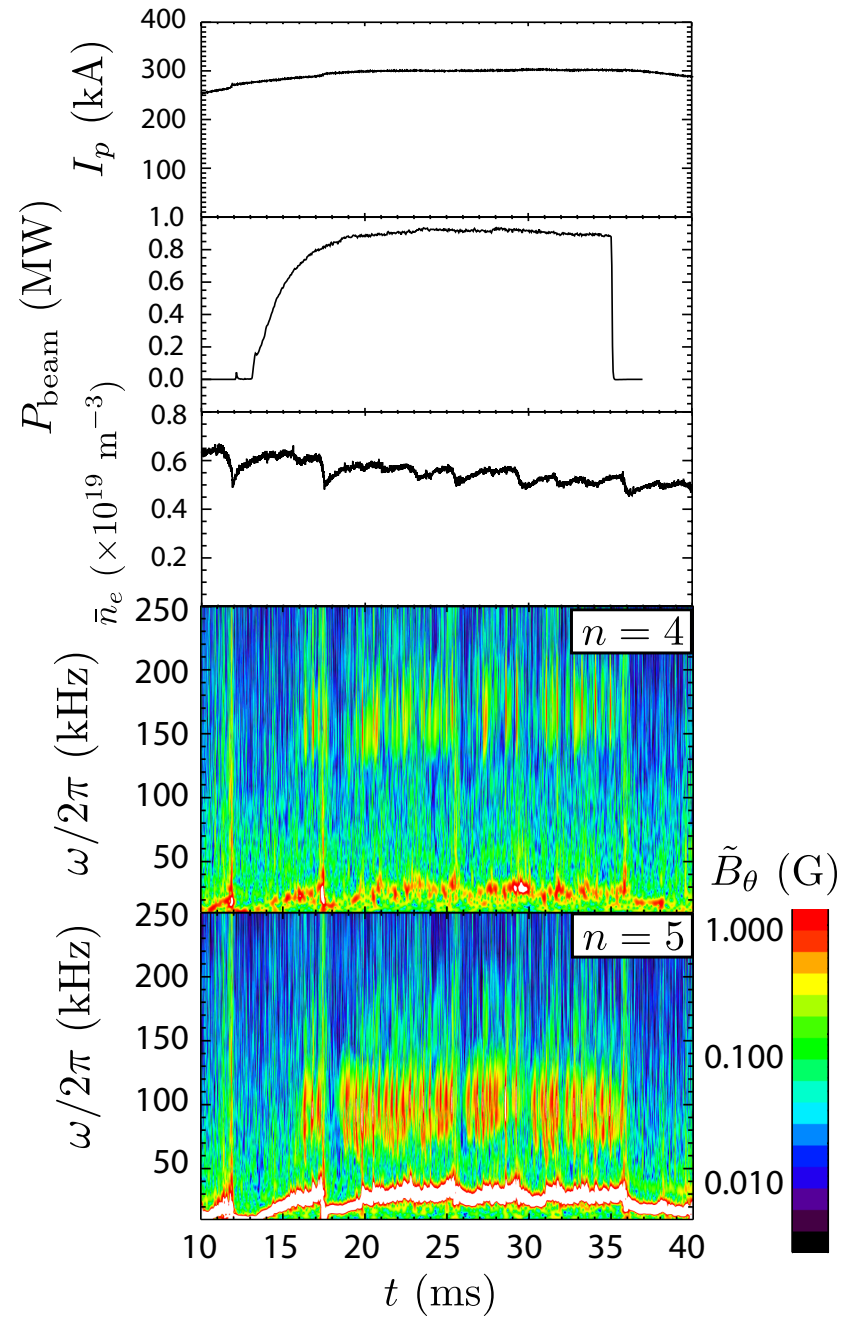
Bursting (EPM) modes are observed

Bursting modes are observed ≈3 ms after beam turn-on.

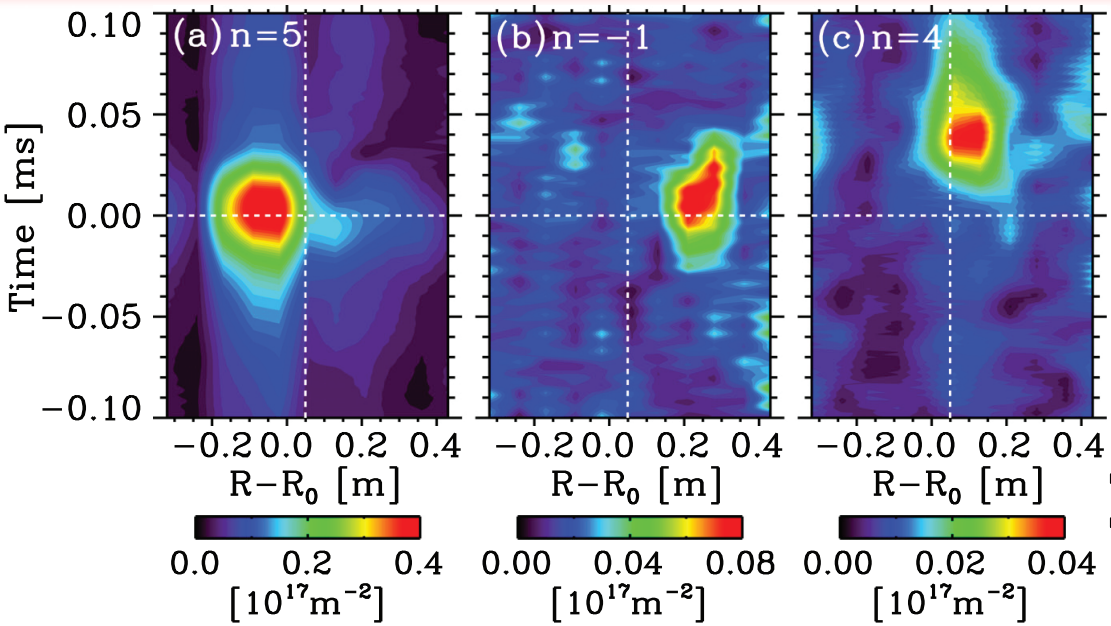
$$f_{n=5} = 65 \text{ kHz}$$

$$f_{n=4} = 140 \text{ kHz}$$



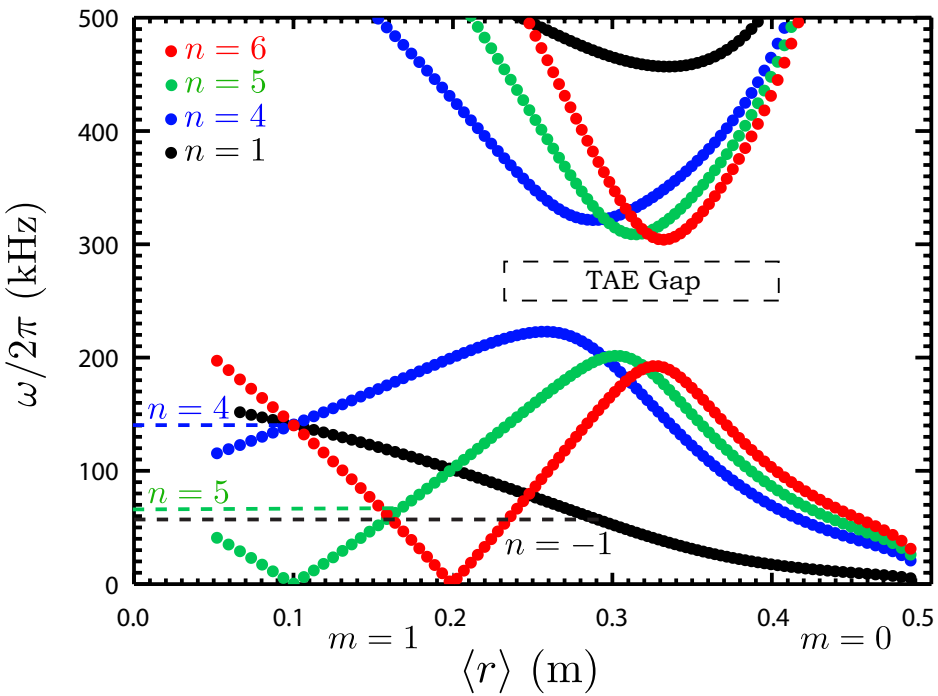


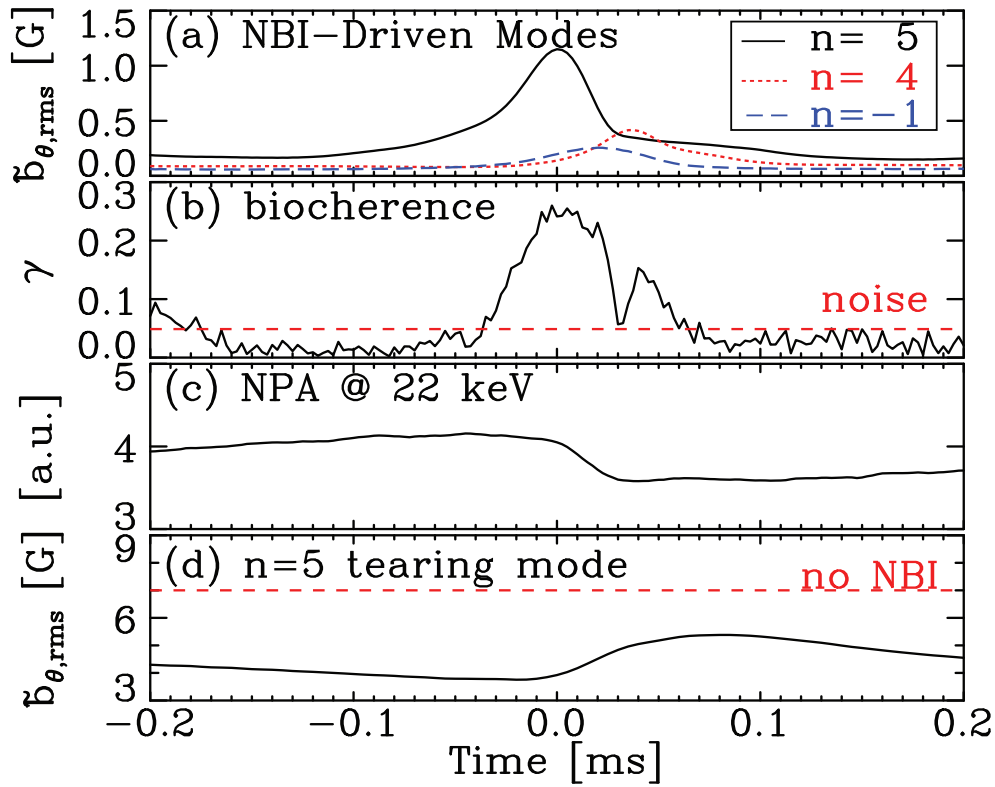
Bursting (EPM) modes are observed



The FIR interferometer measures different radial locations for each mode. confirms continuum picture.

The modes happen in succession every time, with the n=5, then the n=4, mediated by the n=-1.





L. Lin 2013

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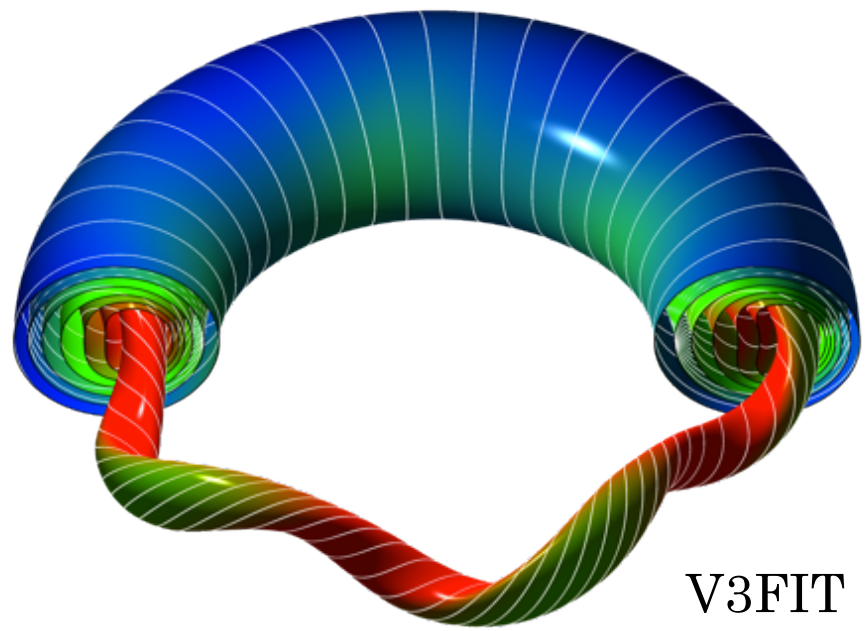
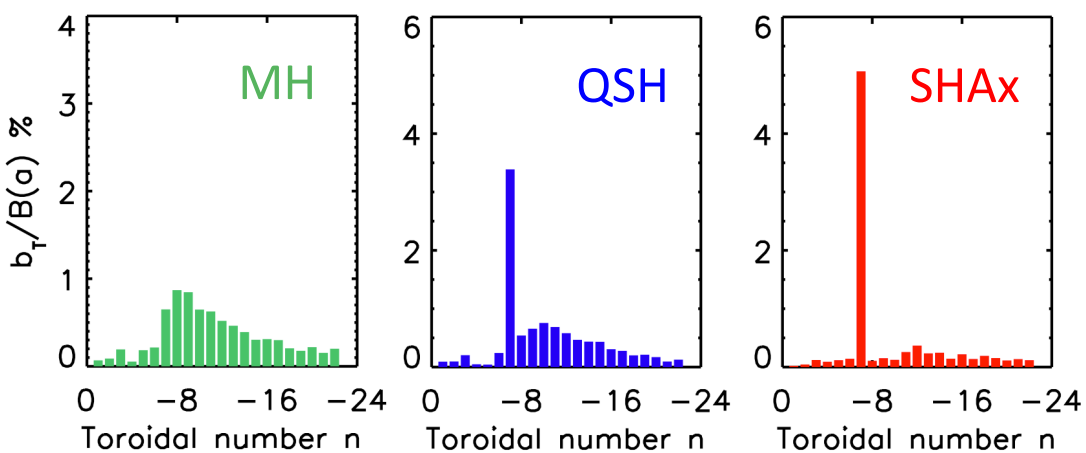
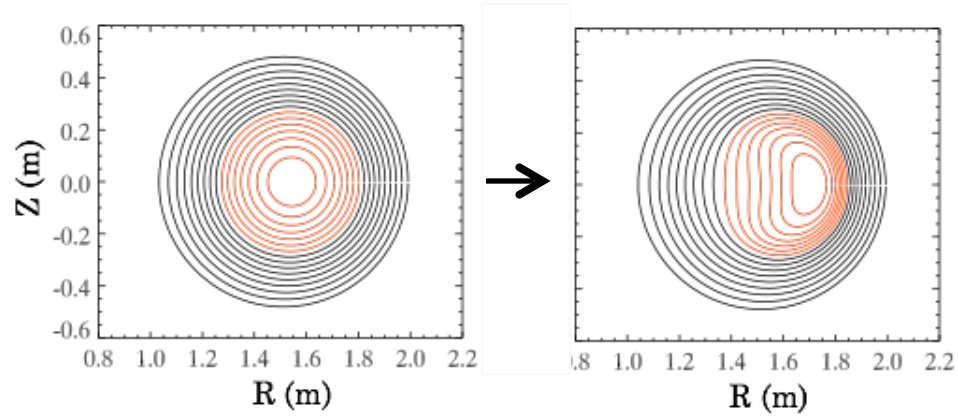
Plasmas transition to a Single Helical Axis (SHAx) equilibrium

- Multi-Helicity (MH) – Standard axisymmetric case with multiple tearing modes at comparable amplitudes.
- Quasi-Single Helicity (QSH) – Large (5-10% B_0) magnetic island winding around deformed initial axis.
  - "Axisymmetric" axis is also helical
- Single Helical Axis (SHAx) – X-point disappears; magnetic island becomes magnetic axis.
  - Flux surfaces follow dominant mode in the core
  - Circular flux surfaces at the edge
  - Secondary modes reduced; stochasticity reduced





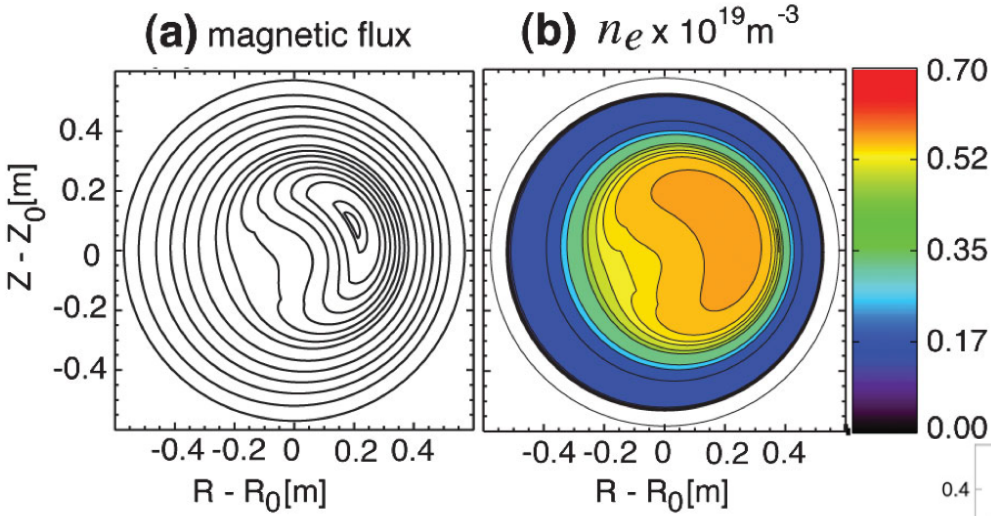


R. Lorenzini *et al.* Phys. Plasmas (2009)

3D Equilibrium is observed on multiple diagnostics

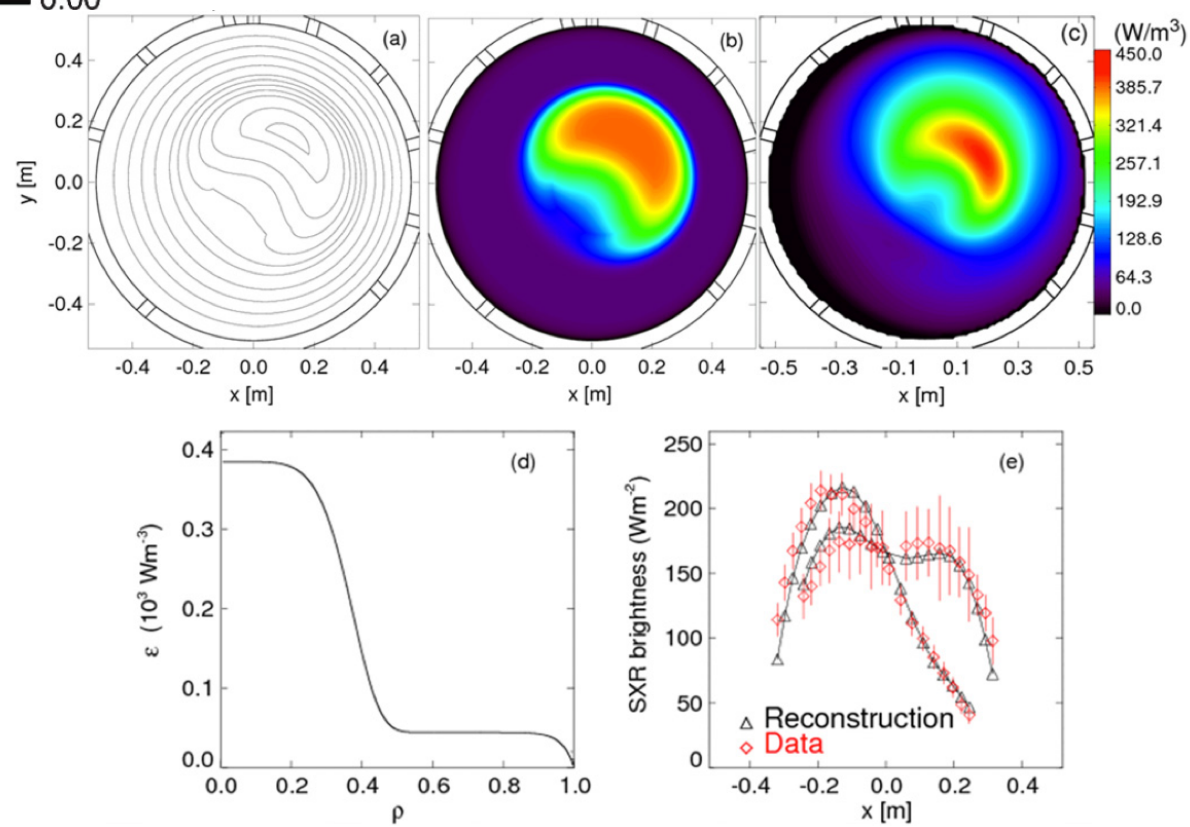
W. F. Bergerson *et al.* PRL (2011)

F. Auriemma et al. Plas. Phys. CF (2011)



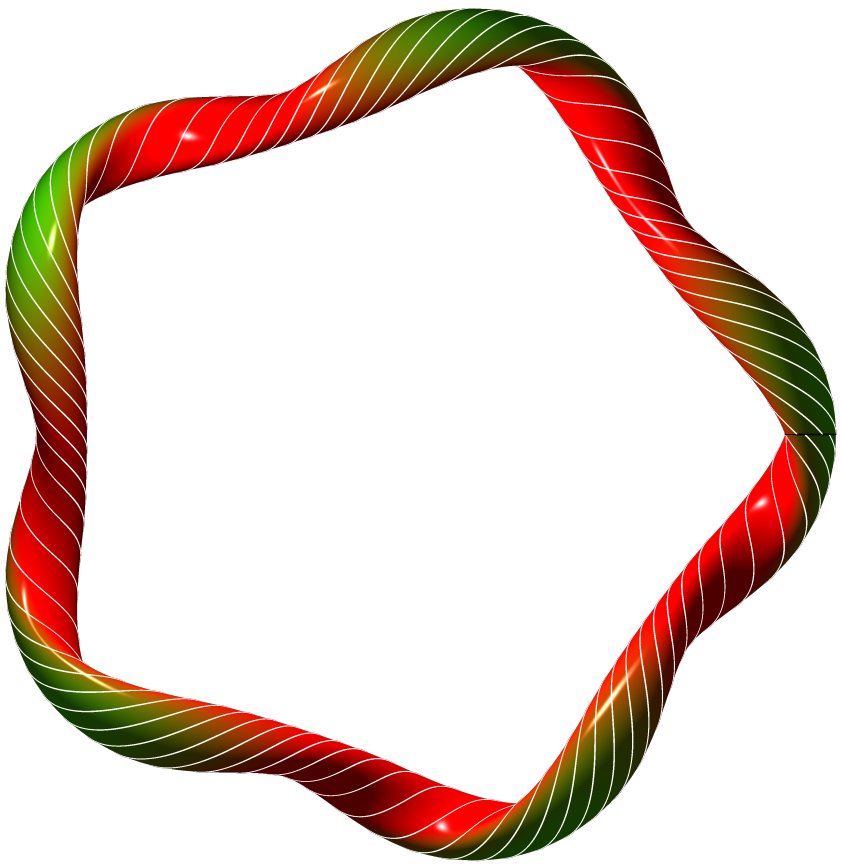
Interferometer and NCT-SHEq

Soft X-Ray Emissivity and NCT-SHEq

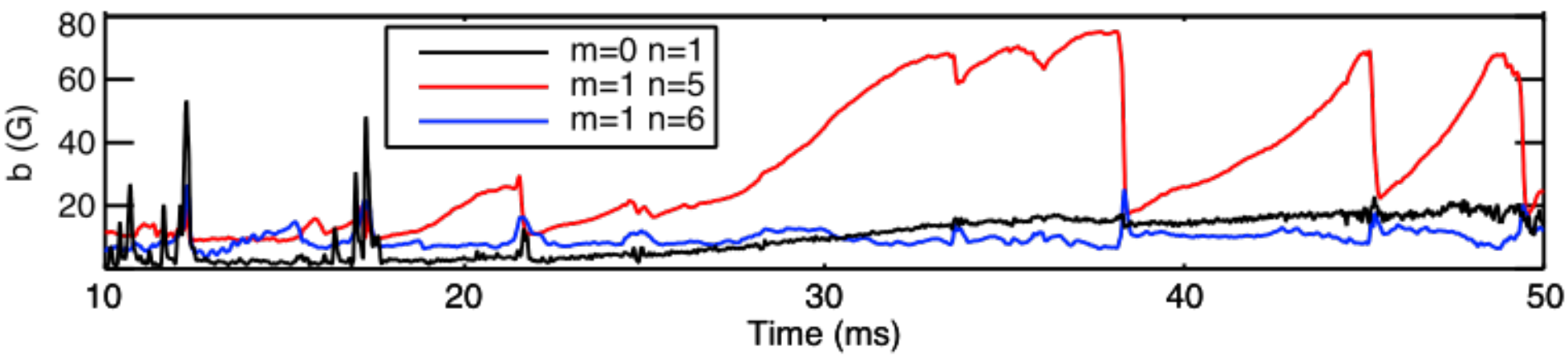


- **Interferometer-Polarimeter**
  - 11 chord FIR laser system observes shifted density structure.
- **Soft X-Ray**
  - 2 camera Soft X-Ray emission system observes similar structure in emissivity.

SHAx has several favorable properties

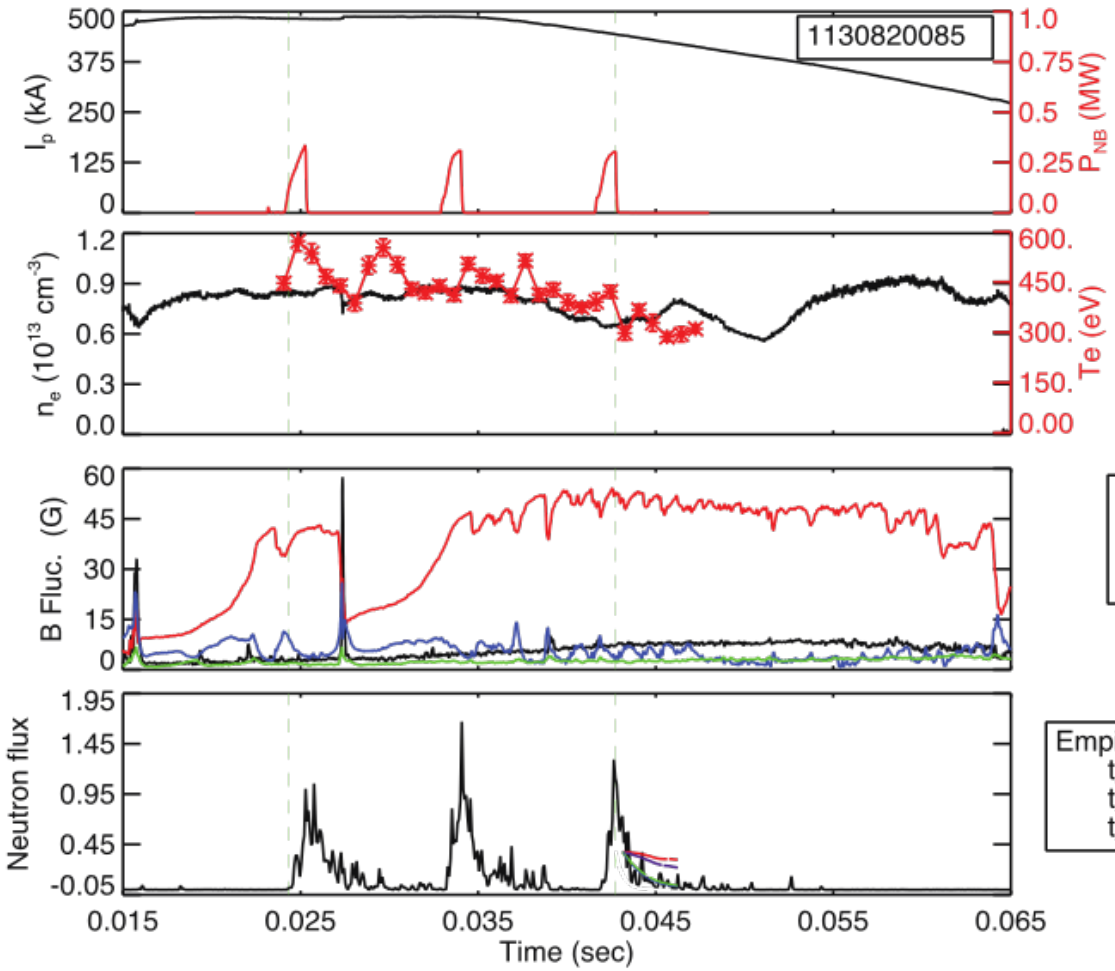


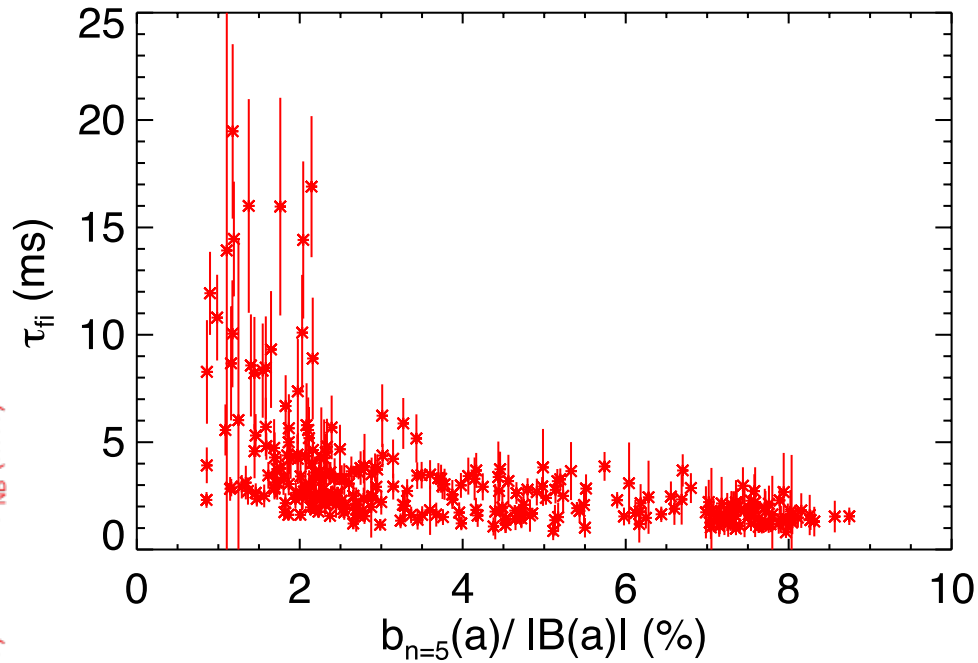
- **Reduced secondary mode amplitudes**
  - Reduces stochasticity outside of the core
  - Refered to as "Improved Confinement-Like" conditions in circular edge
- **Improved energy confinement**
  - Temperature increase observed on-axis at RFX
  - Energy confinement time increased by ~50% on MST
- **MHD activity reduced**
  - No sawtooth (m=0) events
  - EPM-like mode not seen on edge magnetics



Measured confinement time is significantly shorter in SHAx plasmas

Neutron decay rate experiment performed as with MH MST plasmas. Multiple beam blips per shot



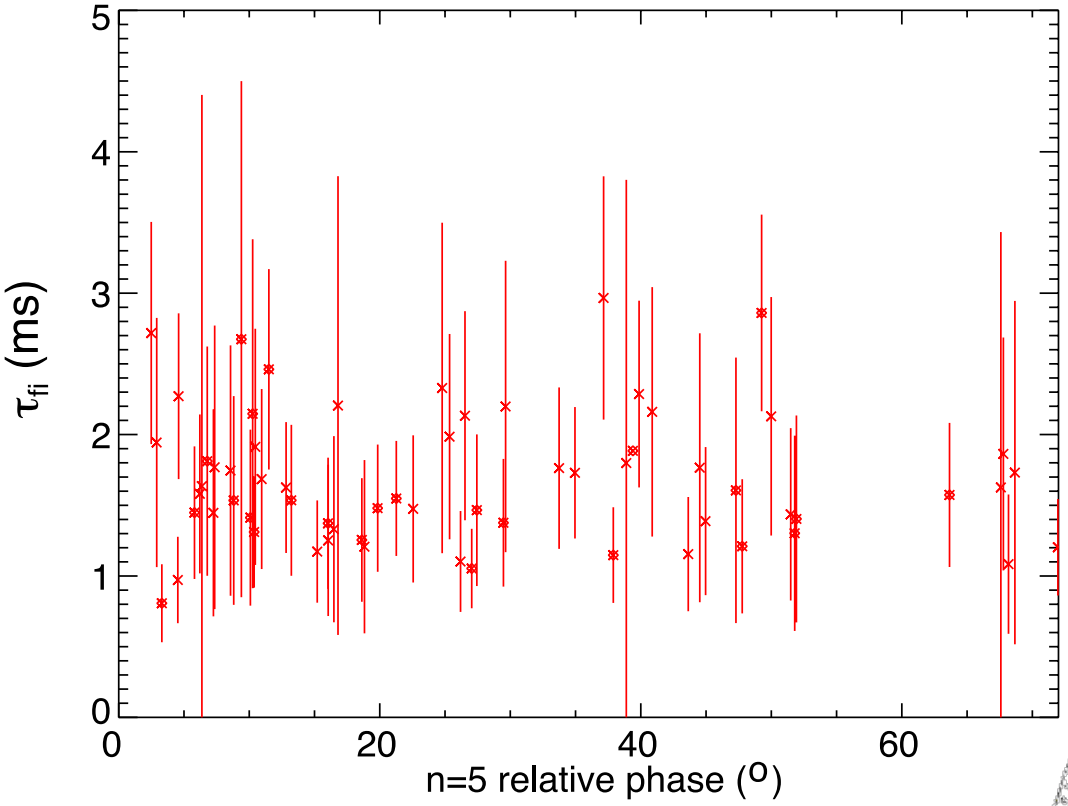


Confinement time is very short!

$$\tau_{fi} \approx 1 - 3 \text{ ms}$$

Decreased stochasticity AND confinement.

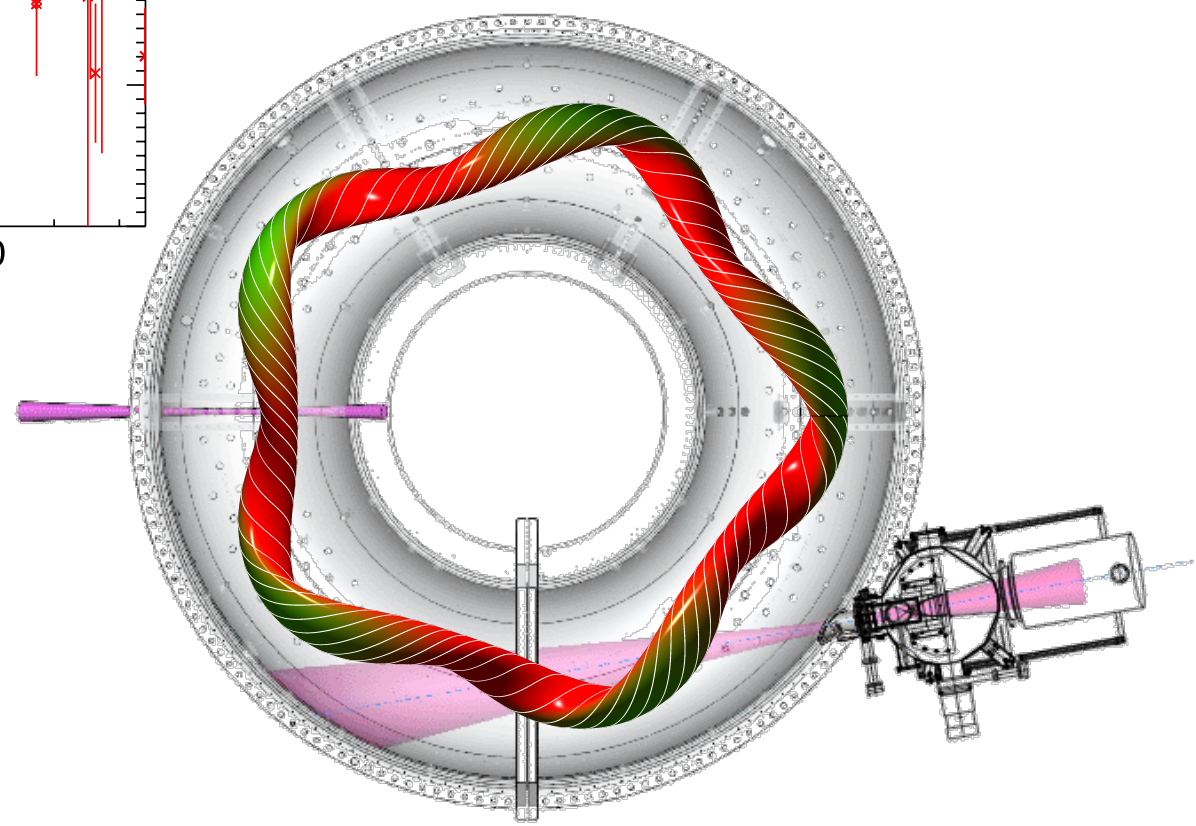
Shorter confinement time has several possible explanations



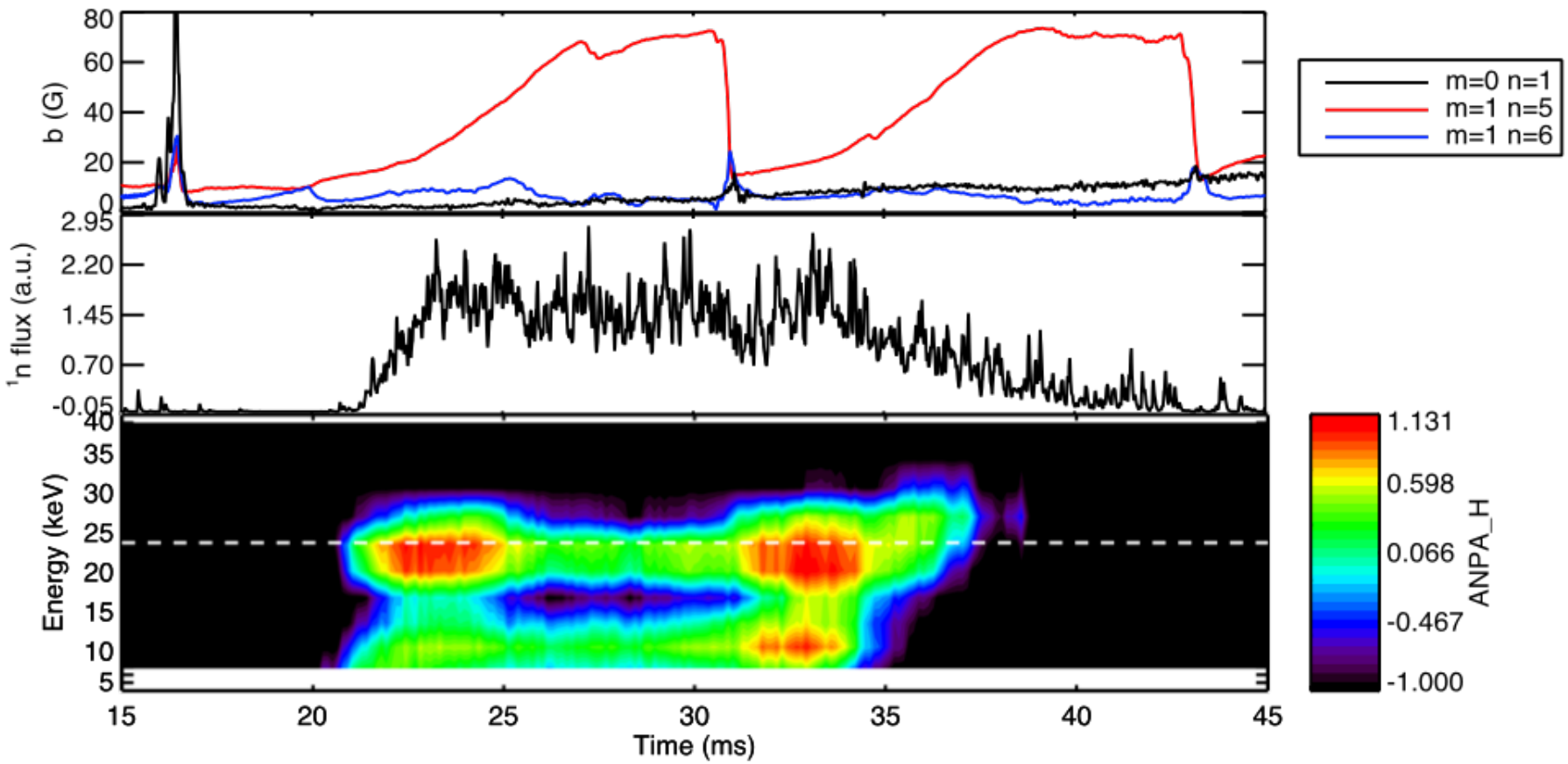
Neoclassical Transport

SHAx state is similar to a non-optimized stellarator.

Not related to phase angle of mode locking.

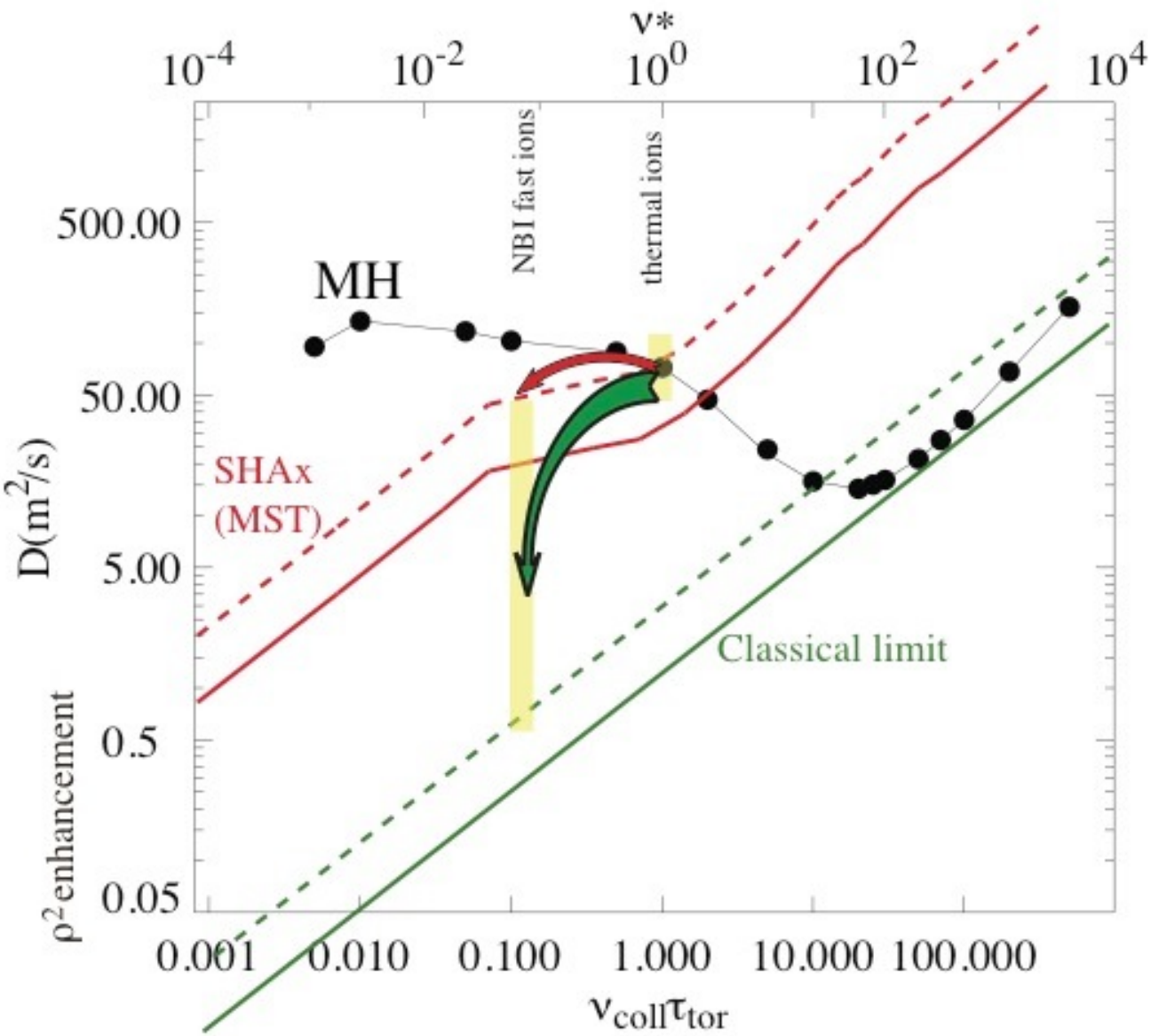


NPA signal drops at SHAx onset, neutron signal does not



- **NPA signal drop at beam energy**
  - Tangential viewing chord: $v_{||}$ in the core of an axisymmetric plasma
  - Neutron signal persists
  - Beam is deposited **somewhere**

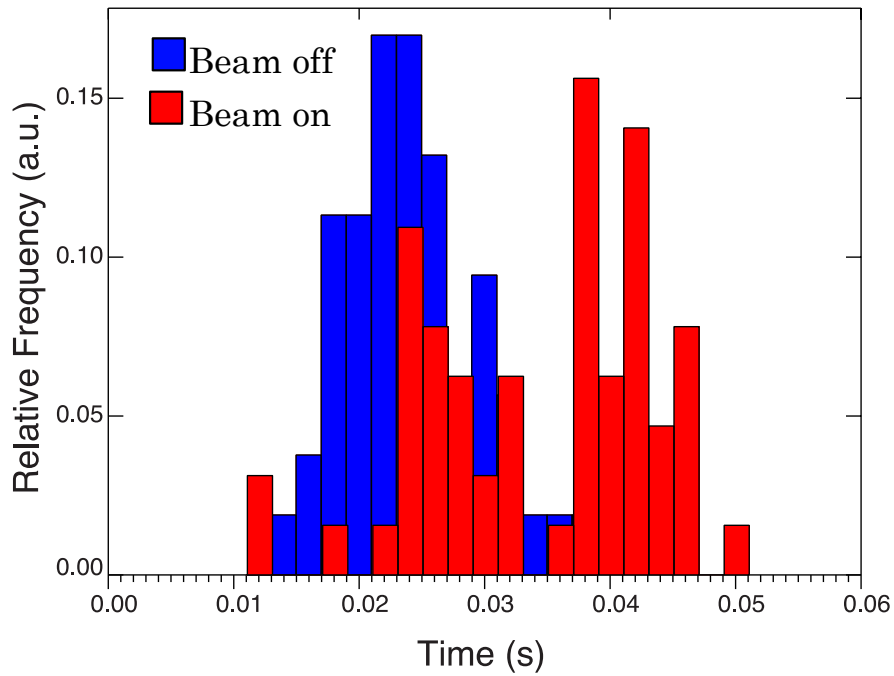
Stochastic immunity leads to neoclassical confinement



- High poloidal field means MH equilibria are near-classical
  - Low PS diffusion
  - No banana regime
  - No plateau
- Diffusion governed by effects from stochastic fields at low collisionality
- Large gyroradius renders fast ions immune to stochasticity and islands
  - Classical limit in MH plasmas
  - Neoclassical in SHAx

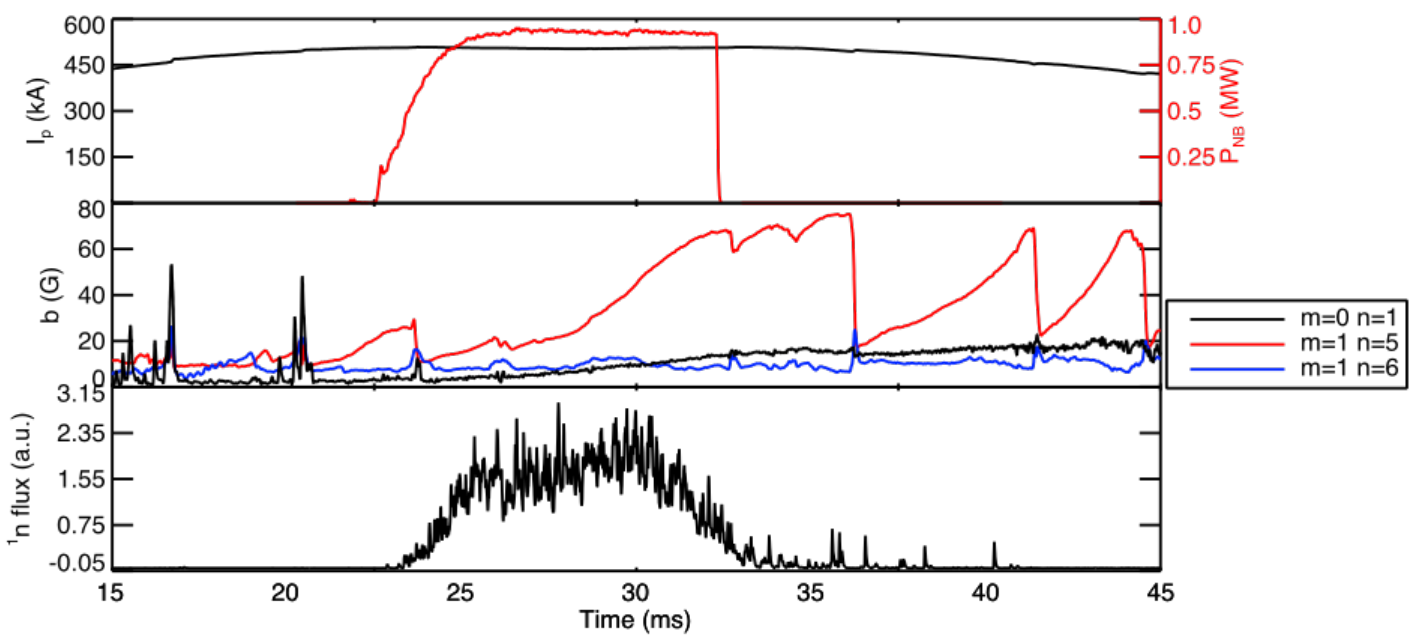
(Extrapolation from RFX calculations)

NBI slows transition to QSH

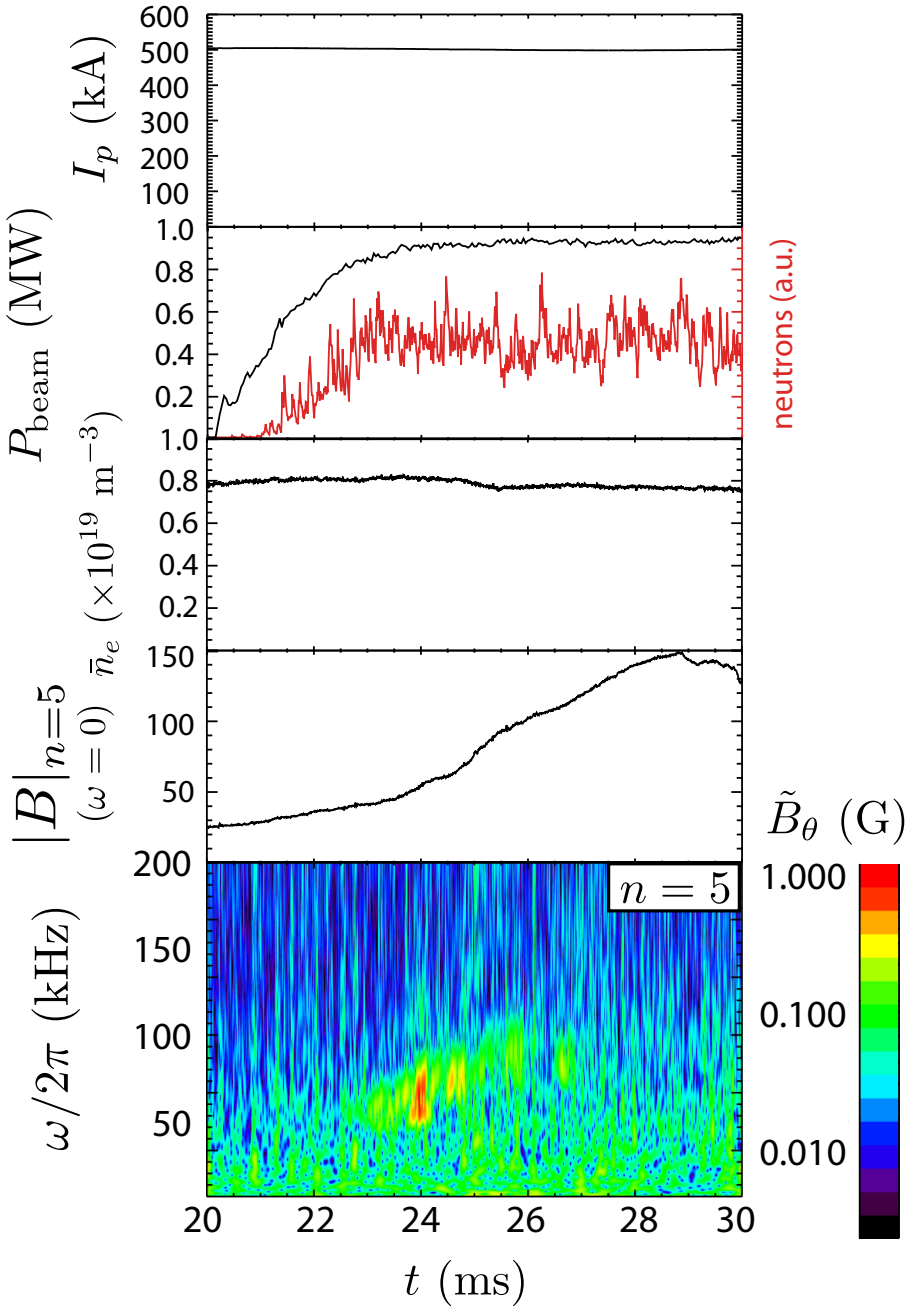


On-axis NBI slows transition to 3D state

- Several possible mechanisms
  - Decreases tearing mode amplitudes
  - Increases tearing mode rotation
- Beam ions and dominant mode interact strongly



SHAx supresses EPM bursts



- EPM bursts are present in non-reversed plasmas, but disappear at SHAx onset.
- Frequency upshift seen before bursts terminate.
    - Plasma rotation locks as QSH ramps up - not a Doppler shift effect.
- Disappearance is possibly a result of poor confinement

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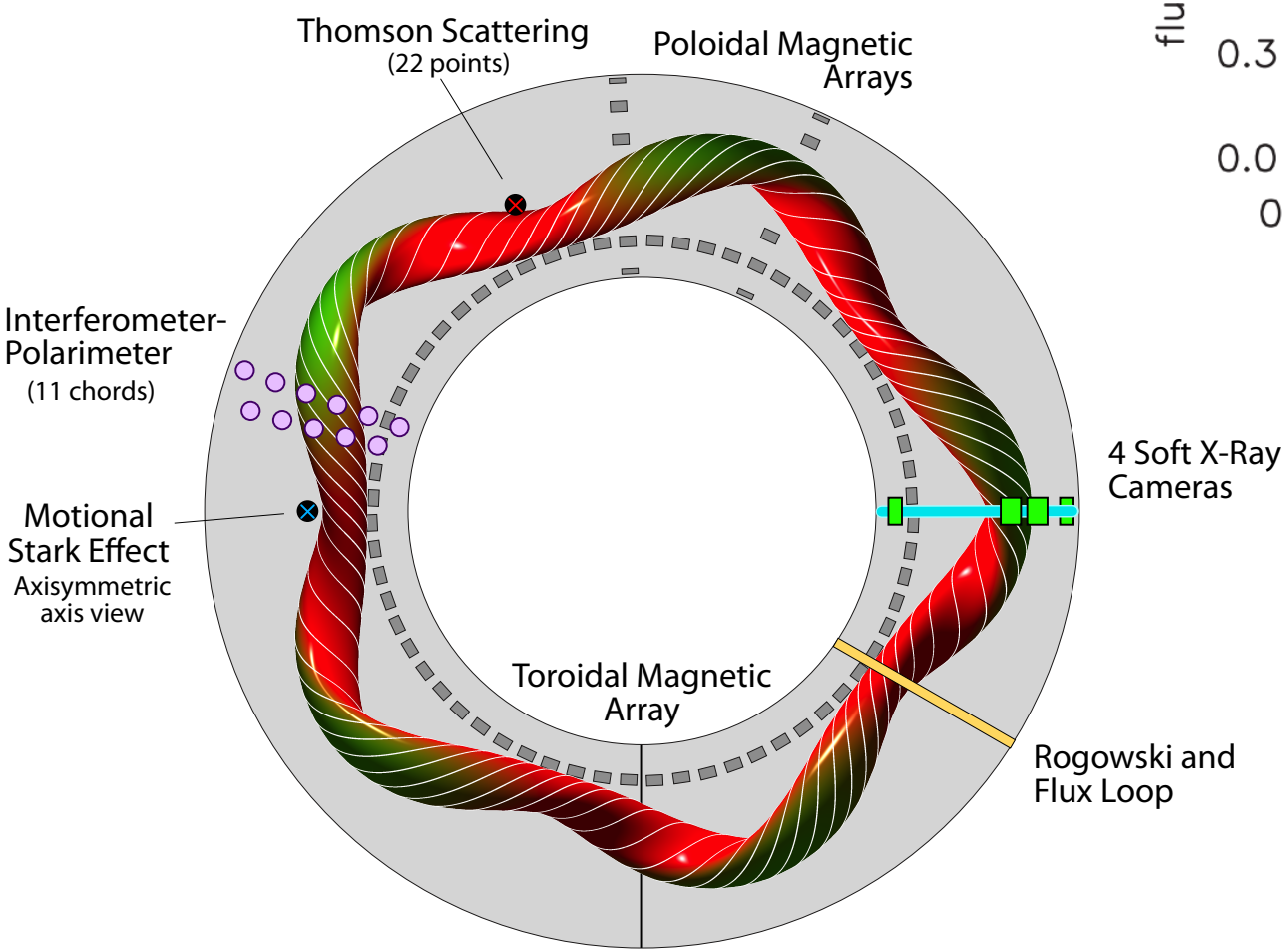
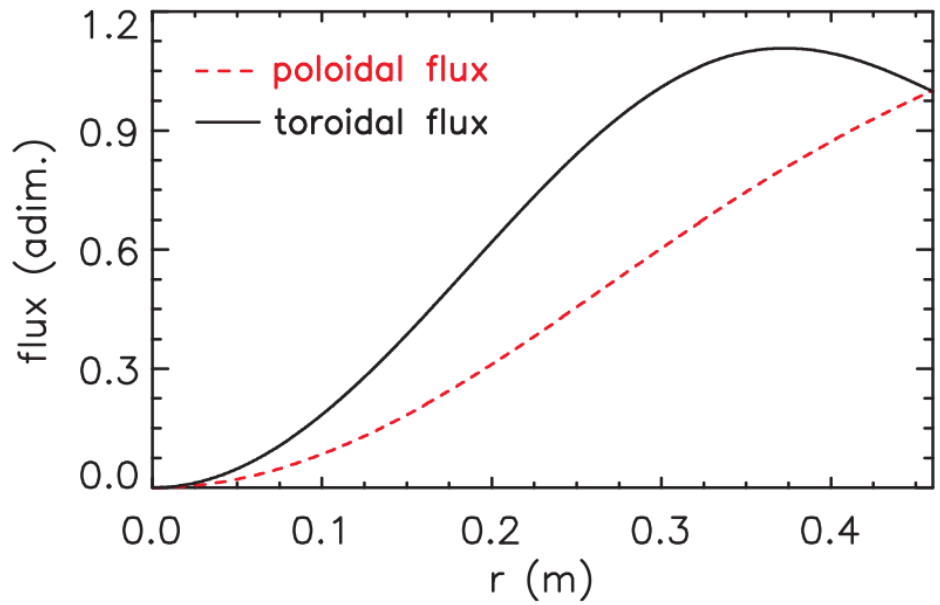
Challenges for analysis on MST

Fixed diagnostics are not set up to characterize helical equilibria.

Helical axis locks with random phase shot-to-shot.





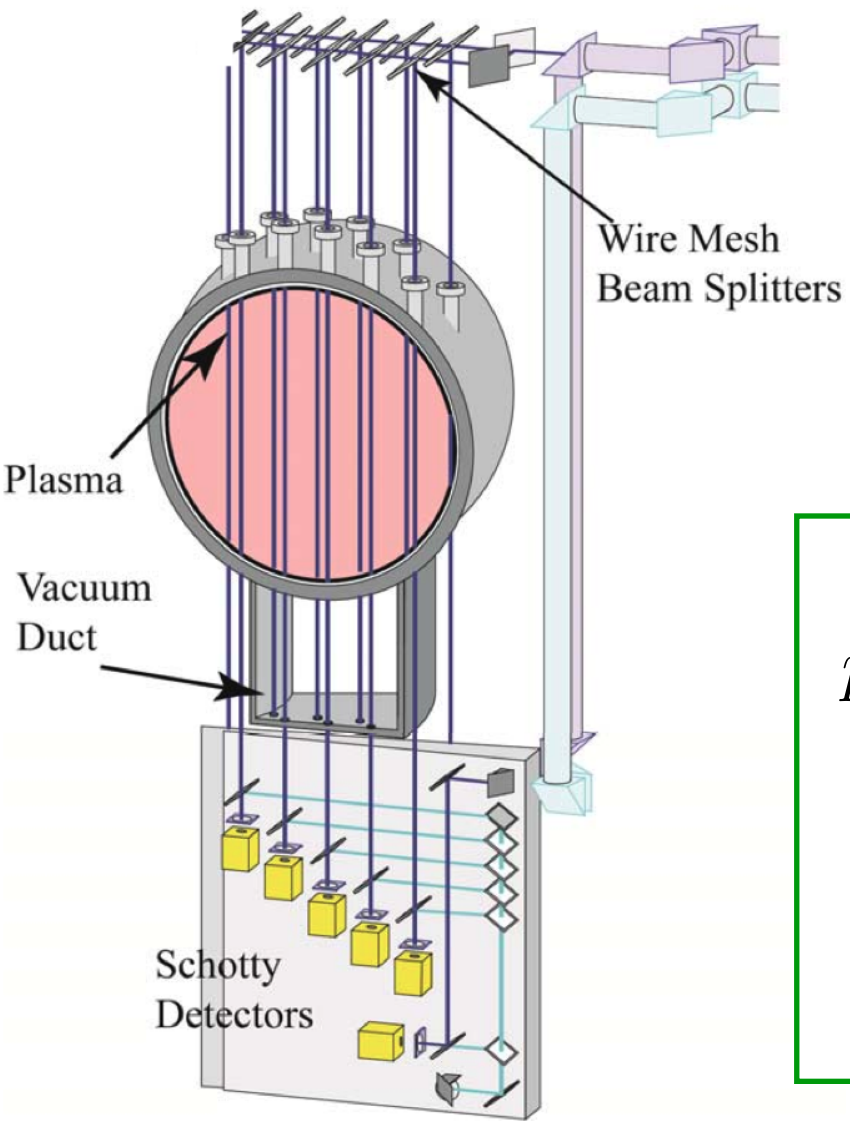
Many codes use toroidal flux as the coordinate. Toroidal flux is not monotonic, rendering it a poor flux coordinate for the RFP

$$\frac{\psi'_{tor}(0)}{\psi'_{tor}(a)} < 0 \qquad \frac{\psi'_{pol}(0)}{\psi'_{pol}(a)} > 0$$

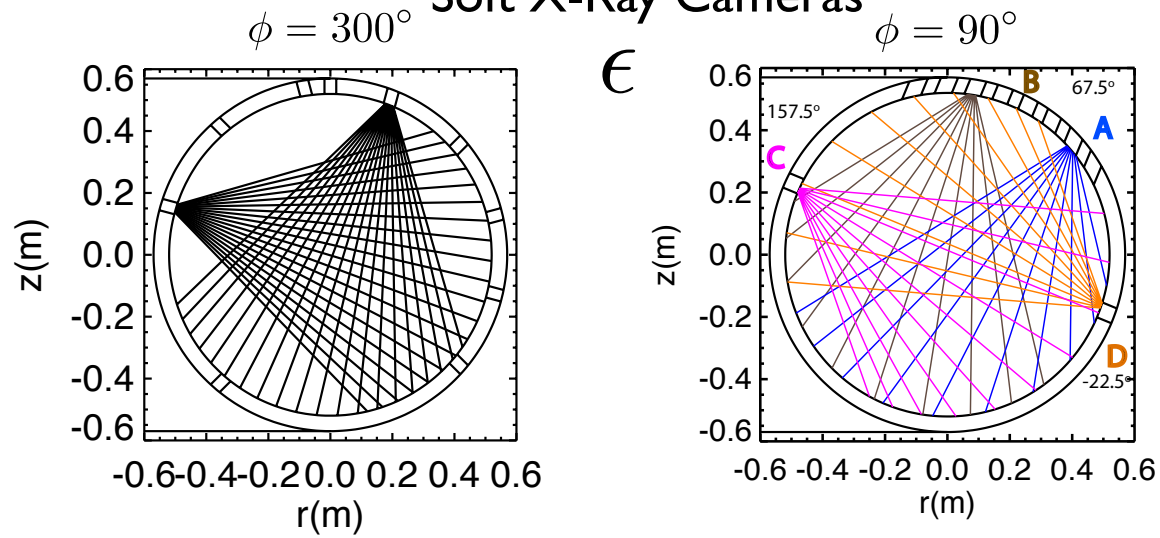
V3FIT Motivation: Construct 3D equilibria using many diagnostics

FIR Interferometer-Polarimeter

$\bar{n}_e$ $\overline{n_e B_z}$



Soft X-Ray Cameras



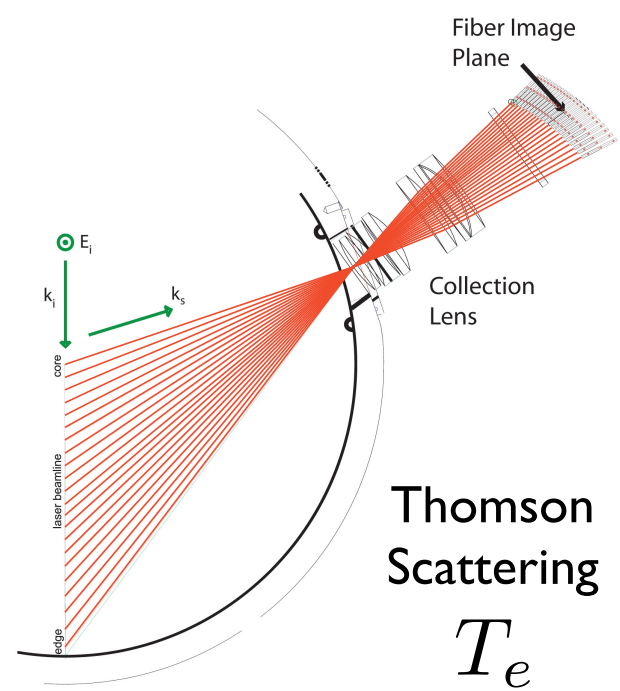
$$\mathbf{j} \times \mathbf{B} = \nabla p$$

$$p_e = k_B n_e T_e$$

Assume:

$$p_i \propto p_e$$

$$\epsilon = \epsilon(\psi)$$



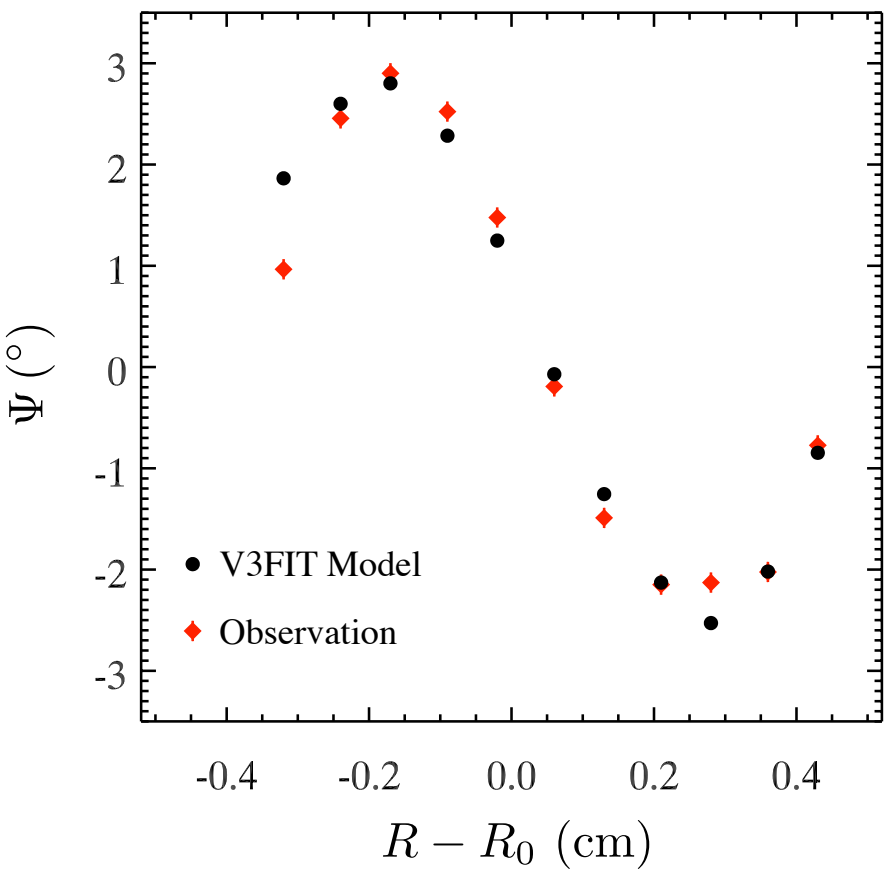
Thomson Scattering

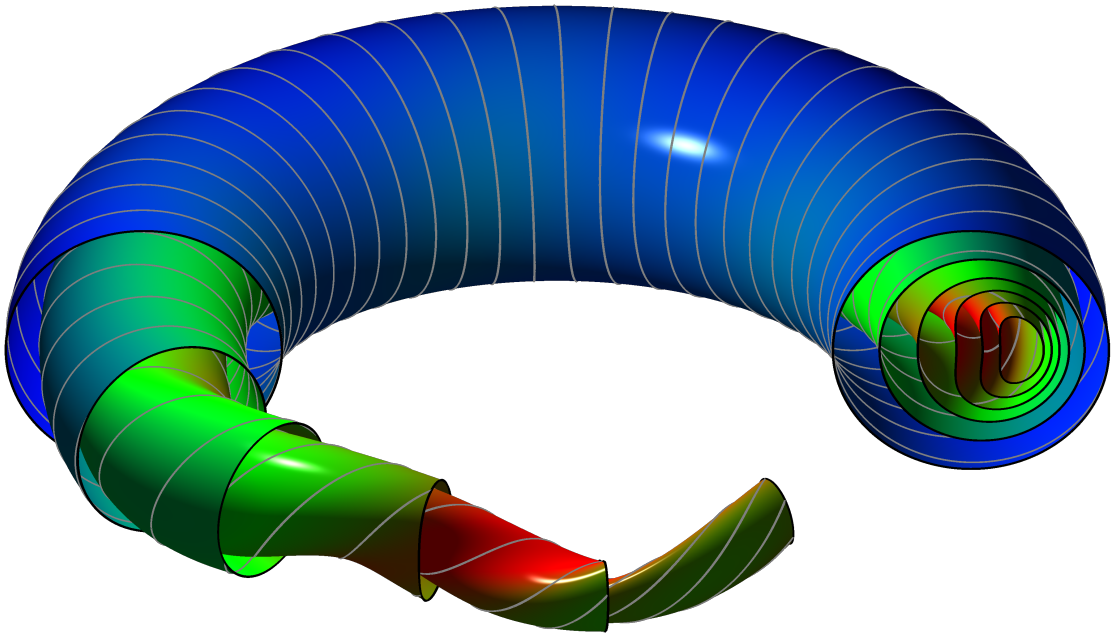
T_e

Fixed Boundary SHAx Reconstructed

Fixed boundary (no external currents specified) V3FIT reconstructions have been performed for MST, and match diagnostic signals well.

FIR Polarimeter (Faraday Rotation)

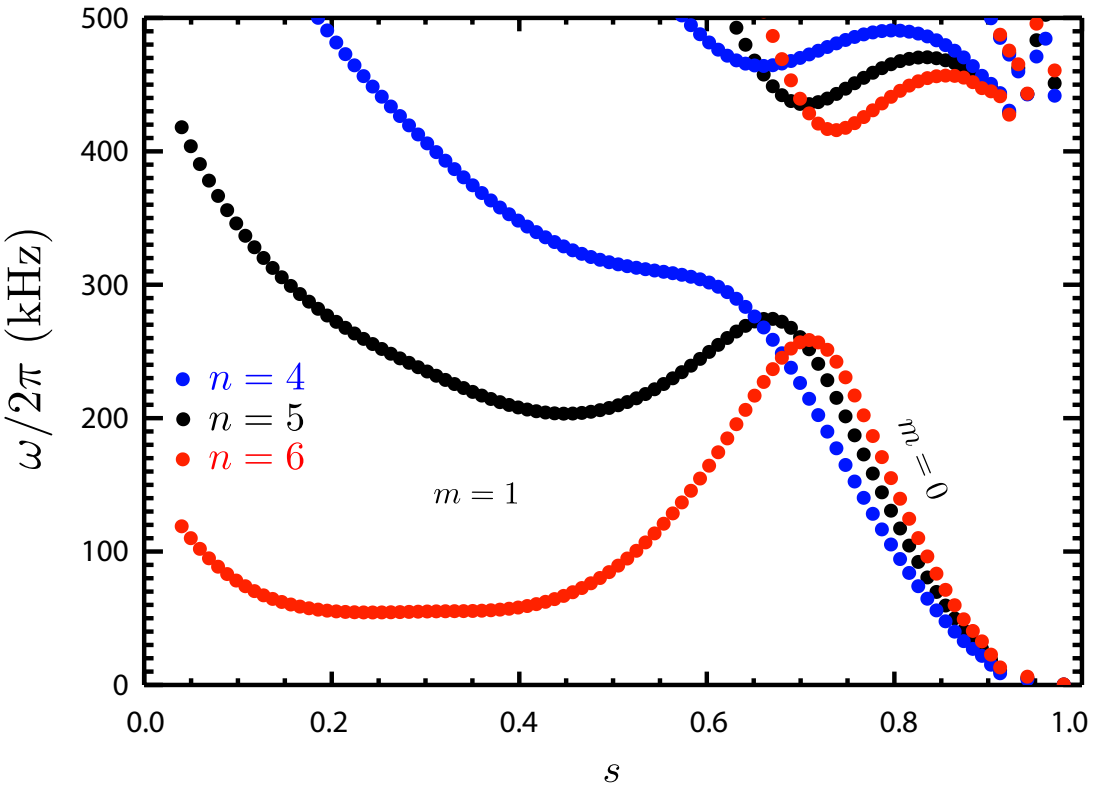


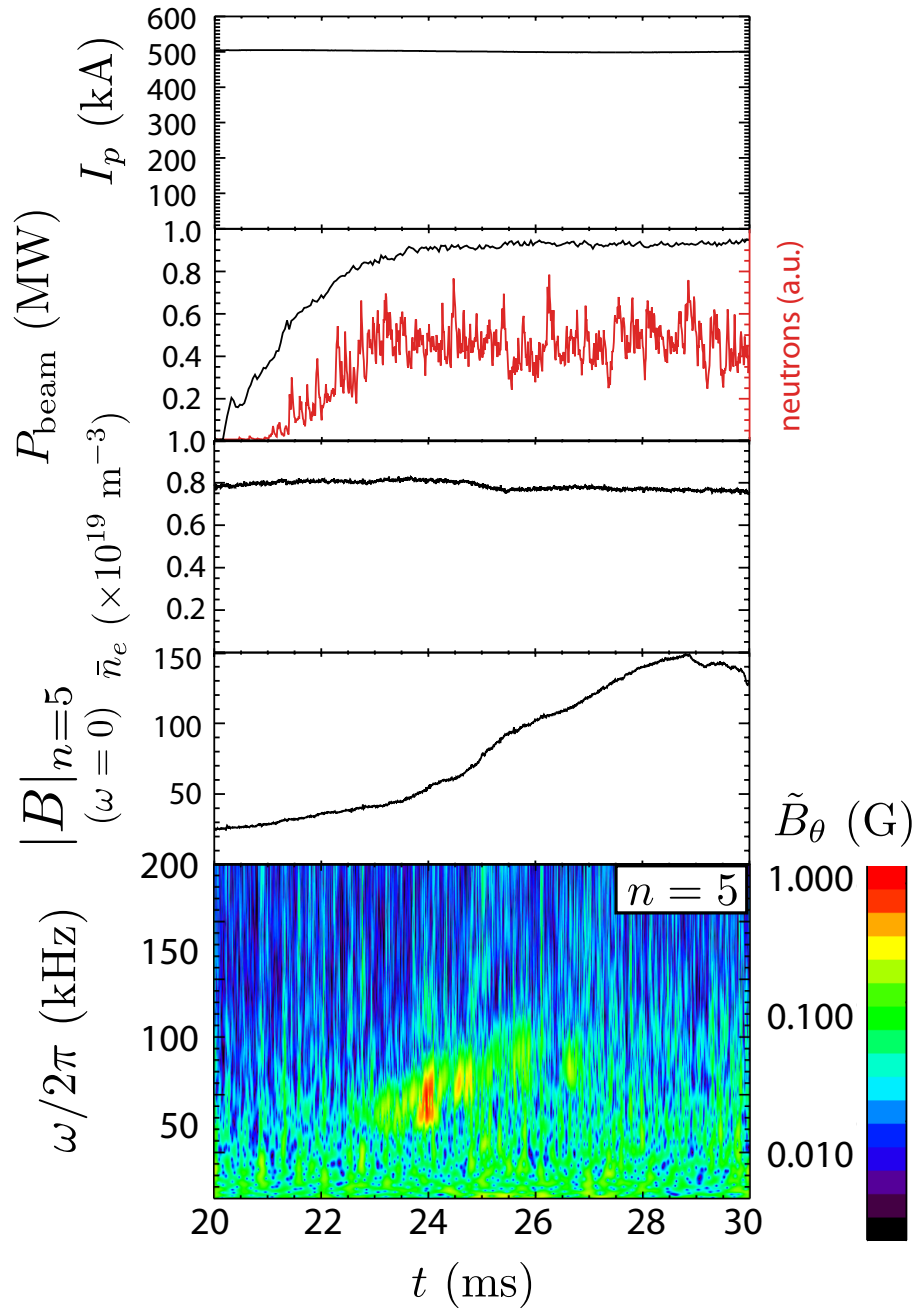


- Correction factor of 0.4 for detected helical magnetic signals is used.
  - ~60% of detected field must be coming from helical shell currents
  - Determined by solving the forward problem with V3FIT using NCT-SHEq equilibria
  - Not an ideal solution - should determine shell currents simultaneously

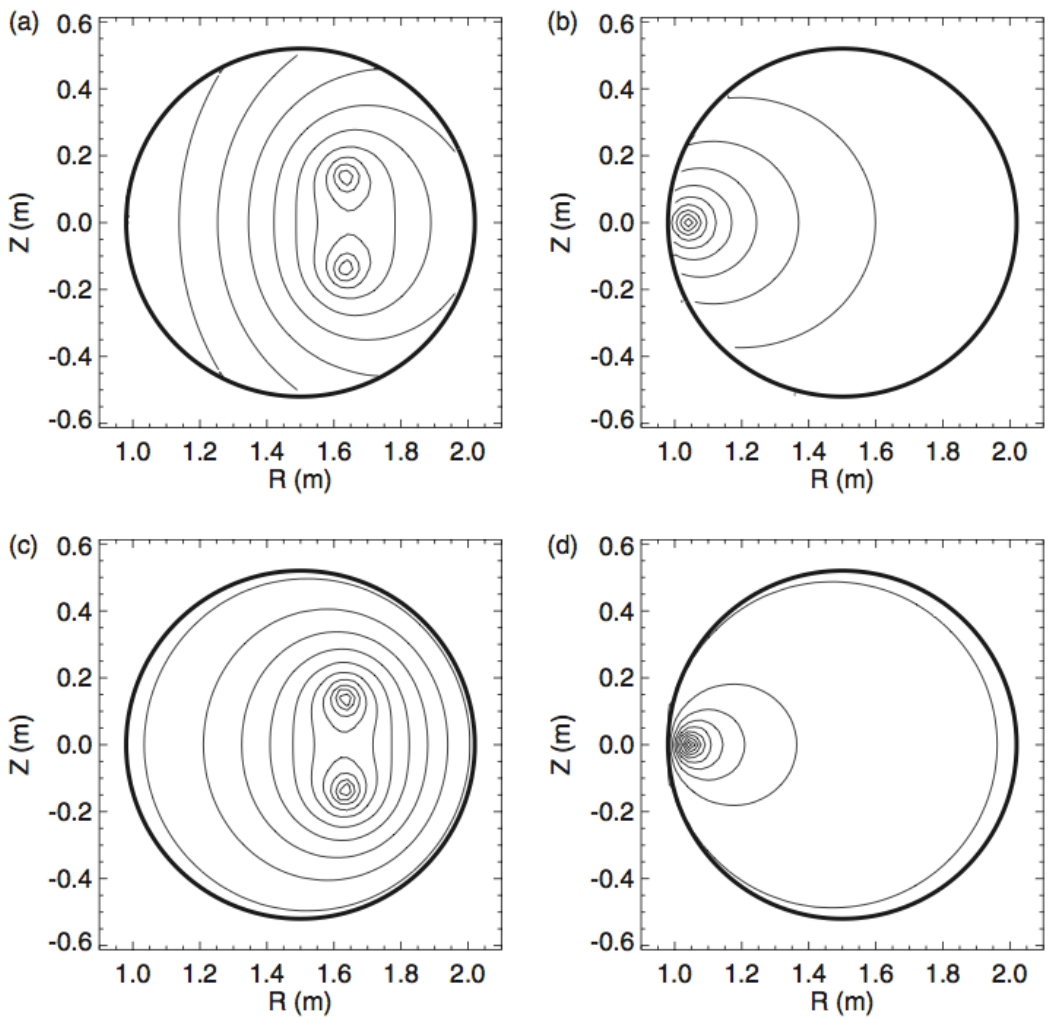
3D Equilibria used with STELLGAP

n=5 continuum "peels upward" in frequency during SHAx transition, eventually losing the resonance.





Moving to Free Boundary reconstruction of SHAx equilibria



Eddy currents in the shell sustain the equilibrium. Their magnitude is non-uniform and unknown, especially in 3D.

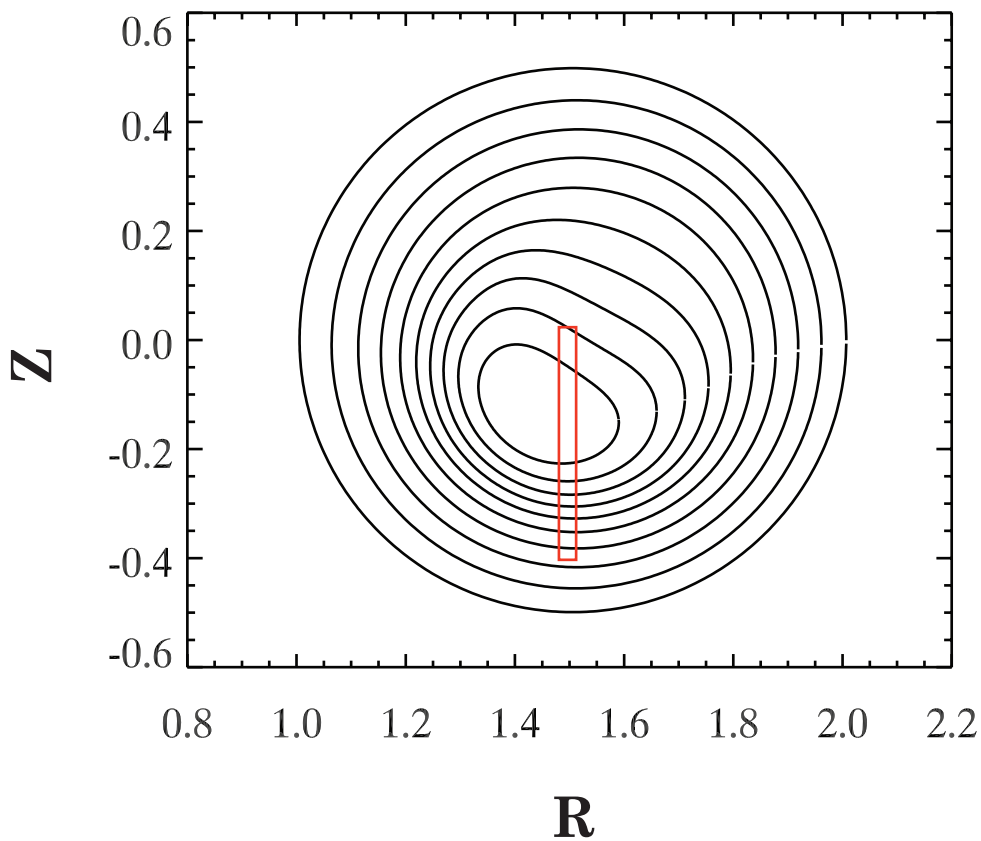
- Effort to obtain a free boundary equilibrium reconstruction in 3D is underway
- V3FIT can vary parameters in VMEC
- Free boundary VMEC specifies external current geometry, with magnitude as a parameter
- Shell currents can be cast as external current filaments
- Combined, allows dynamic determination of unknown shell currents by running free-boundary V3FIT/VMEC reconstructions
  - In Progress…

Active feedback locking system used to target the optimal toroidal phase

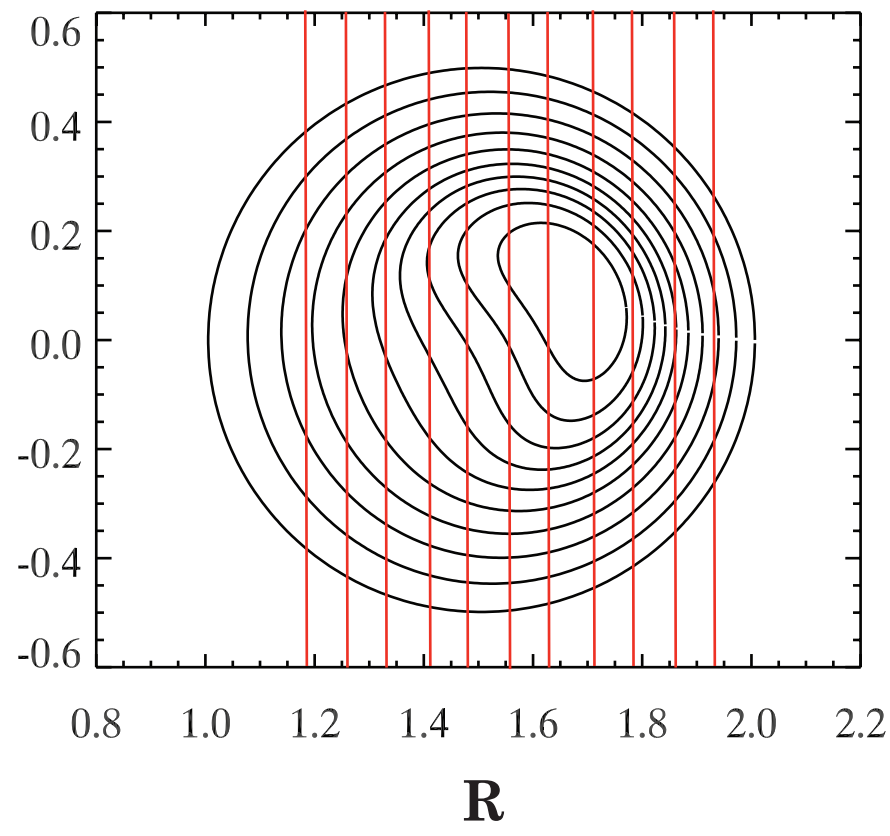
A small error field is applied to lock SHAx in the optimal phase (determined using V3FIT).

Error field is then removed after SHAx onset.

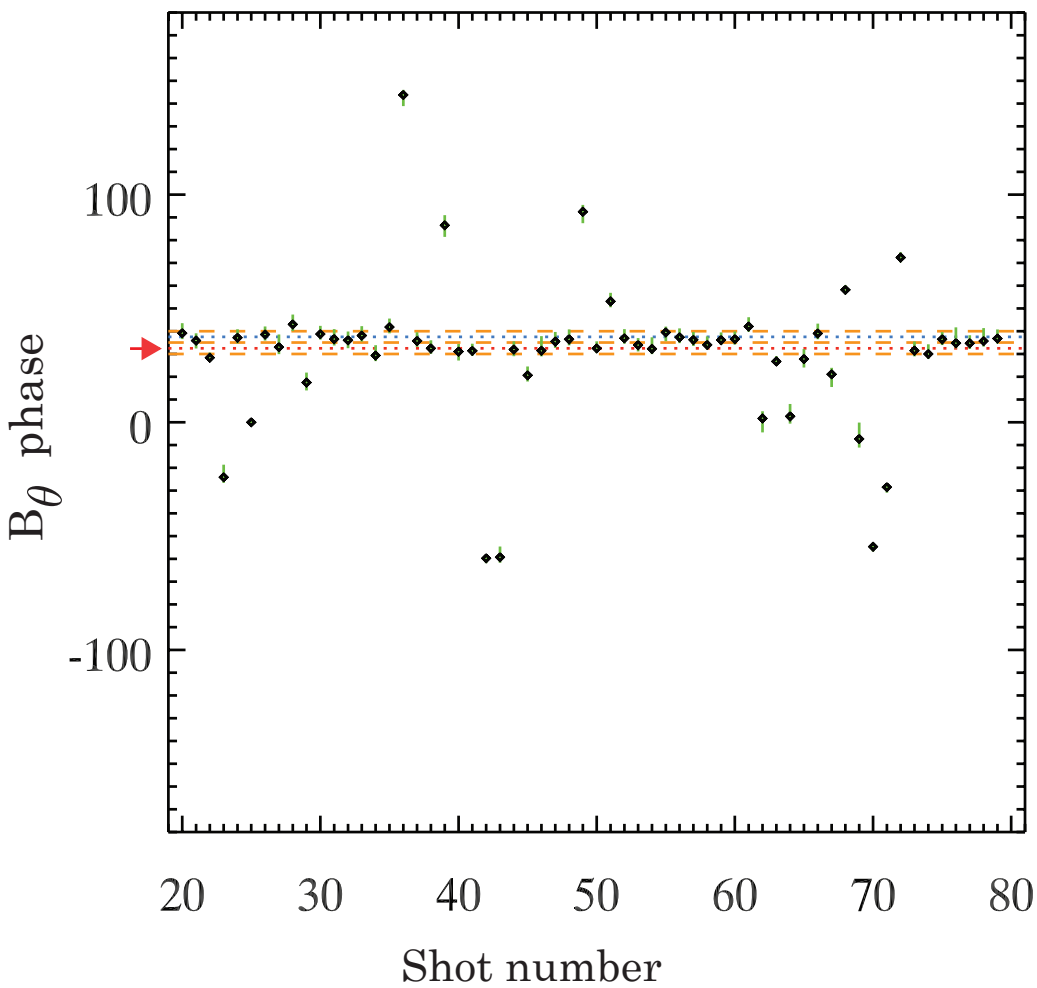
Thomson

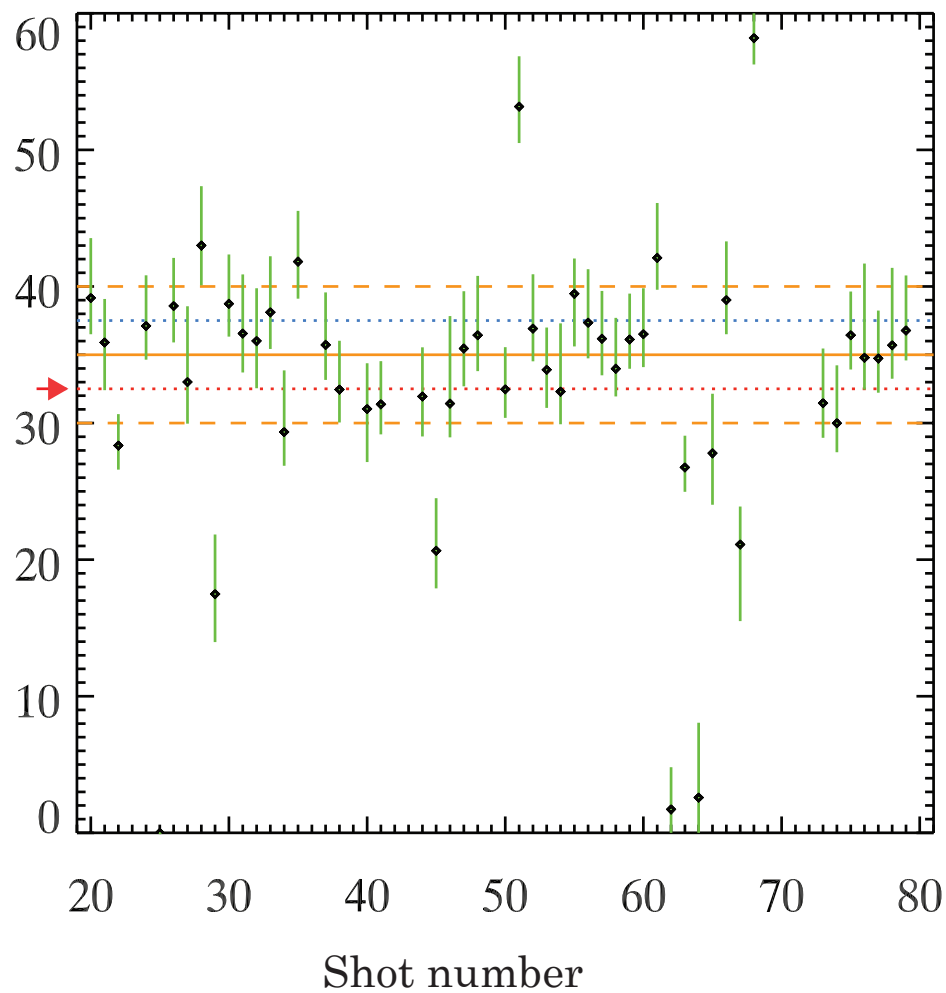


FIR



Results of locking are pretty good





Using VMEC equilibria and Future Work

Hardware

- Increase phase-space coverage of NPA (or NPAs), install fast ion loss detectors.
- Optimize locking system to fix mode phase reliably.

Software

- VMEC equilibria already useable by a multitude of codes
  - Full orbit modeling, beam deposition and transport (HFREYA), Alfvén wave calculations (AE3D/STELLGAP)
  - Need to expand other codes for MST use
- Produce reliable 3D free boundary equilibria

Summary

- In MH RFP discharges, fast ions are near-classically confined despite stochastic fields and poor thermal particle confinement.
  - Presence of fast ions enhances mode rotation, suppresses tearing mode amplitudes, and drives EPMs
- MST RFP's undergo transition to 3D equilibrium through the growth of the dominant n=5 mode.
  - Beam injection delays SHAx onset
- Confinement of fast ions in SHAx is markedly poorer than in MH cases.
  - Along with Alfvén continuum change, alters and suppresses EPMs
- V3FIT reconstructions to determine helical plasma characteristics are progressing